ENGLER-BUNTE-INSTITUT

HANDBOOK

Ministry of Water And Irrigation

BRACKISH WATER DESALINATION IN WATER-SCARCE REGIONS

THE JORDAN VALLEY

SMART MOVE

DVGW

KIT Karlsruhe Institute of Technology

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Contributors & Partners

This Handbook was elaborated within the contributions of the DVGW-Research Center at the Engler-Bunte-Institut (KIT) to the BMBF funded SMART-MOVE project which seeks to find sustainable management solutions of available water resources in the Jordan Valley with partners from Jordan, Palestinian Territories, Israel and Germany.

Sustainable **M**anagement of **A**vailable Water **R**esources with Innovative **T**echnologies - **M**anagement **O**f Highly **V**ariable Water R**E**sources in semi-arid Regions

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LIST OF ABBREVIATIONS

DOC	Dissolved Organic Carbon
EC	Electrical Conductivity
LJRV	Lower Jordan Rift Valley
LSI	Langelier Saturation Index
MCM	Million Cubic Meter
NF	Nanofiltration
PA	Polyamide
PES	Polyether Sulfone
RO	Reverse Osmosis
SDI	Silt Density Index
SHMP	Sodium Hexametaphosphate
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TWW	Treated Waste Water

TERMINOLOGY

Brackish Water	water with a salinity ranging between that of fresh water (TDS < 500 mg/L) and seawater (TDS > 30,000 mg/L)
Brine	concentrate stream of a crossflow membrane desalination system. It is a waste product containing most of the TDS and chemicals added in the process.
Flux	the rate of permeate transported per unit of membrane area. Unit: liters per square meter and hour (l/m^2h)
Fouling	accumulation of material (organic, inorganic, biofouling) on the membrane surface or in the membrane pores. Membrane Fouling can lead to a severe flux decline and to a decrease of water quality.
Permeability	a membrane parameter, which is defined as flux divided by operating pressure. Unit: liters per square meter and hour and bar (l/m^2hbar)
Permeate	the product water of the desalination process. It is very low in TDS and therefore chemically aggressive (corrosive)
Recovery	the ratio of product water flow rate (product quantity) over the feed flow rate (input quantity). $Y = V_{Permeate}/V_{Feed} \cdot 100\%$
Salt Rejection	describes the ability of a membrane to act as a barrier for certain ions. It is defined as 1 minus the ratio of permeate concentration over feed concentration times 100%. Typical RO membranes have a salt rejection of greater 95% for all ions.
Scaling	the precipitation of salts due to oversaturation
SDI	also FI (Fouling Index); commonly used index to assess the fouling risk due to particulate matter and colloids
LSI	index to assess the calcium carbonate solubility for brackish waters. $LSI = pH - pH_s$ (pH_s is the value of pH if the solution were in equilibrium with calcium carbonate

1. INTRODUCTION

The present Handbook has been elaborated within the contributions of the EBI to the BMBF funded SMART joint project. SMART aims to develop an integrated water resources management for the Lower Jordan Rift Valley (LJRV) with contributions from universities, ministries and private companies from Jordan, Palestinian Territories, Israel and Germany. The DVGW-Research Center at the EBI (KIT) is a research facility for water chemistry and water technology. The EBI has extensive experience on membrane desalination technologies and has been conducting research projects on reverse osmosis (RO) and nanofiltration (NF) for almost two decades.

The characteristics of the LJRV pose unique challenges for water management. Climatic conditions are highly variable and perpetual water sources are scarce and declining in the region. Therefore, additional water sources are of high value to meet the demand. The brackish water aquifers of the LJRV are such an additional long-term water source. Given appropriate treatment, the water can be utilized as high quality irrigation and drinking water supply. Today, membrane desalination is a well-established state of the art technology to appropriately treat brackish ground waters at favorable economics.

In Jordan, the privately run farming business has already started utilizing the brackish ground water sources over a decade ago. Small scale RO-units installed on farms are used for treating the brackish groundwater to meet agricultural irrigation quality demands and supplement existing water sources. RO-Systems are supplied by Jordan based companies which use imported parts from major membrane desalination companies. The existing market is unregulated and implements systems at very competitive capital costs.

This handbook seeks to provide a base level knowledge about the implementation, design and operation of RO/NF-Systems for brackish water desalination and add to the already existing knowledge base in the LJRV. It specifically takes into account the unique characteristics present in the LJRV. It also seeks to provide context of brackish water desalination with regard to best practice considerations, economic considerations as well as sustainability considerations. Any membrane desalination technology produces a more or less concentrated waste (brine). Depending on the applied treatment/disposal, brine can cause a variety of environmental issues, which mainly affect the soil quality and the quality of water in connected aquifers.

This handbook does not replace technical manuals from manufacturers and professional expertise from suppliers but rather aims to supplement these existing knowledge bases to help the end-user understand the main relations and issues surrounding RO/NF-system implementation in order to make better decisions about utilizing membrane desalination.

2. THE LOWER JORDAN RIFT VALLEY

The Lower Jordan Rift Valley is in many ways a unique area on this planet. It is the lowest place on earth and its long cultural history and importance is manifested by political tensions, which still have not been completely resolved today. The region is defined by water scarcity and with Israel, Jordan and the Palestinian Territories, the LJRV is comprised of three administrations, which have vastly different capabilities and resources for the management of their local water supply. Water consumers in the LJRV have to cope with the challenges of a semi-arid to arid climate with a high variability in water availability and water quality. The majority of the rainfall is concentrated in the period from October to April and the total amount can vary significantly from year to year. In addition to the seasonality and the strong interannual variability of the rainfall, there are strong topographic differences, which lead to a concentration of the rainfall to the mountainous areas. In the southern part of the LJRV, total annual precipitation amounts to only 50 to 150 mm. In contrast, the total annual evaporation capacity amounts up to 2600 mm. Hence, the main water source is surface and groundwater which are replenished by precipitation water from the highlands east (Jordanian highlands), west (Judean Mountains) and north (Hauran Plateau). [1]

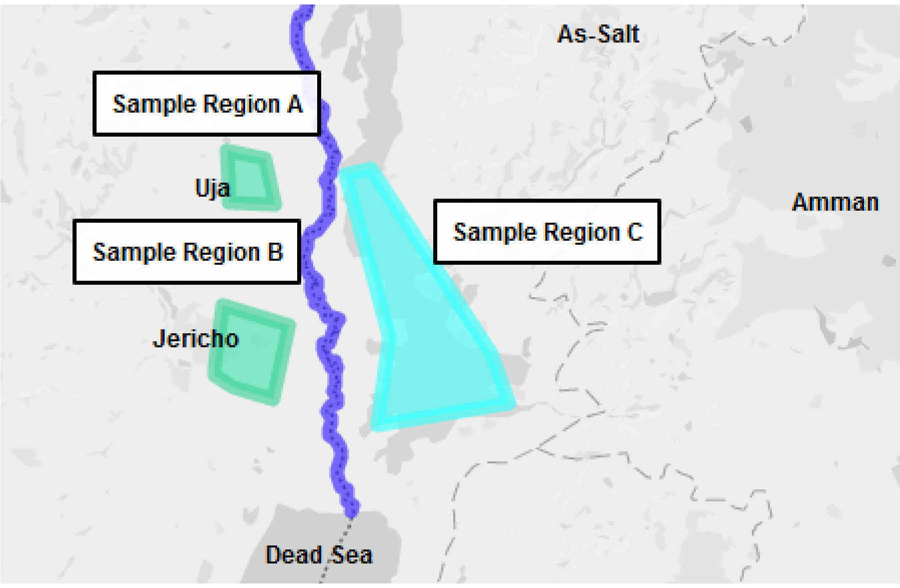


Figure 1: Sample areas of brackish groundwater aquifers in the LJRV

For the elaboration of this handbook, two areas in the southern part of the LJRV, east and west of the Jordan River were in focus (Figure 1). In both areas, the main economic activity is agriculture, which is highly dependent on the availability of freshwater. In Jordan, farmers can extract a limited water volume from the King Abdullah Canal, which was built to distribute water from the northern border through the valley to the Dead Sea. In the southern area, water availability is reduced due to the extraction in the north. For supplementation of their water supply, farmers have begun to utilize the brackish groundwater aquifer. Wells are from 100 m up to 170 m in depths. By blending the saline groundwater with the sweet water or by desalinating the saline water, farmers significantly increased their water stock. This holds true especially for the dry season where desalination allows for cultivating crops throughout the year. In the southern LJRV, more than 50 RO-Units with an average design capacity of 30 to 40 m^3/h have been deployed already (as of 2016). Other options for additional water supply, such as import from other areas, are challenging economically and politically. Hence, the present and future development of the area is highly dependent on the management of current water sources, which includes the management of the brackish water aquifers.

In the West Bank territory, desalination technology has not yet been deployed. But similarly, the water stock for agricultural use can be increased when treating the brackish groundwater for irrigation. An estimated 22 million cubic meters per year of brackish groundwater can be treated in the region according to the respective water strategy. East of the Jordan River, up to 82 million cubic meter could be treated per year. As of 2016, Jordan farmers already treat more than 12 million cubic meter yearly. Considering the total water demand of the respective countries, brackish water desalination plays a minor role nationally but may be an important factor locally and can cut the water deficit significantly (see Table 1). [2]

Table 1: Water availability and demand in adjacent countries in the LJRV according to the respective water strategies; adapted from [2]

	Israel		Jordan		Palestinian Territories (West Bank)	
Year	2010	2020	2010	2025	2010	2022
Inland brackish water desalination (MCM/year)	25	75$^{(1)}$	57	82	0.5	22
TWW reuse in agriculture (MCM/year)	400	570$^{(1)}$	100	247	-	30.6
Total water demand (MCM/year)	1,994	2,596	1,315	1,652	125$^{(2)}$	712
Deficit of water (MCM/year)	129	131	361	470	2	>>2

Abbreviations: TWW Treated wastewater; MCM Million cubic meters

$^{(1)}$2015 value; $^{(2)}$2012 value

However, key toward successful implementation of desalination technology is the awareness of several basic issues of brackish water desalination, which are in need of management. First, maximum extraction of brackish groundwater is limited. Abstraction over the limit generally causes lowering of the groundwater level and/or increased salinity. Second, desalination produces liquid waste, i.e. brine. Brine is a concentrate of the raw water further polluted with chemicals used in the process, e.g. antiscalants. Recharging the aquifer with brine would be likely to cause a continuative increase of salinity. Apart from negative effects on the environment, this would also cause treatment to be increasingly cost intensive. Land application of brine could severely affect the soil and may render it unfit for agricultural use. Brine disposal is therefore a critical part of any brackish water desalination implementation. If not disposed of properly, brine may have lingering negative effects, which are not imminent but break through eventually. Any remediation of damaged environment due to brine is extremely difficult and costly.

From these considerations, it is apparent, that firstly one has to be aware that the extracted groundwater in the LJRV is very valuable and therefore should be used efficiently. This means that desalination systems are best operated with high recovery. Any loss of water due to evaporation should be minimized. Secondly, brine must be removed from the area of application to not damage the local environment long-term. The Dead Sea nearby to the south offers a unique possibility to remove brine from the catchment and implementation area of desalination systems. Thus, it may be possible to sustainably manage brackish water desalination in the LJRV at relatively low cost by a rather simple solution: discharging the brine to the Dead Sea. Further considerations of brine disposal are discussed in chapters 3.6 and 6.

In Jordan, the overall available water for irrigation in the lower Jordan Valley has declined over the past 15 years. Additionally the share of treated wastewater used for irrigation has increased which negatively affects the overall water quality. On the other hand total crop area and productivity has increased as well. This demonstrates some key challenges for the agricultural economy in the Jordan Valley. Declining water availability stresses growth of total crop area and demands further increase of productivity which itself is stressed by declining water quality [3-5]. Brackish water desalination produces high quality irrigation water, which aids in increasing productivity and adds to the total irrigation water available. On the other hand higher costs of desalinated irrigation water reduces economic return from increased productivity, stresses groundwater levels and may reduce overall groundwater quality which of course dependents largely on the applied waste management scheme (brine disposal).

2.1. WATER QUALITY

In 2011 and 2016 water samples from brackish groundwater aquifers in the LJRV have been collected and analyzed at the EBI in Germany. The data helps to extract key issues and challenges about brackish water desalination in the region. Tables 1 and 2 give an overview of the basic water parameters measured from samples of the two areas in Jordan and Palestine.

Table 2: Summary of the analysis of water samples collected in the Jordan Valley (Jordan)

N = 14		Raw Water (Jordan)			
Parameter		(Min - Max)			(Mean)
pH (30°C)		6.2	–	7.0	6.7
El. conductivity (25°C)	mS/cm	3.83	–	11.53	6.20
Barium	mg/L	0.02	–	0.08	0.05
Boron	mg/L	0.81	–	2.20	1.30
Calcium	mg/L	110	–	500	293
Iron	mg/L	0.02	–	0.09	0.06
Potassium	mg/L	46.3	–	137.0	77.9
Magnesium	mg/L	80	–	379	197
Manganese	mg/L	0.002	–	0.100	0.02
Sodium	mg/L	482	–	1335	744
Silica*	mg/L	16.6	–	36.5	22.9
Strontium	mg/L	1.7	–	13.5	5.3
Fluoride	mg/L	0.5	–	2.4	1.2
Chloride	mg/L	885	–	3363	1647
Nitrite	mg/L	2.6	–	7.4	5.1
Bromide	mg/L	1.5	–	47.1	17.9
Nitrate	mg/L	2.9	–	93.0	44.9
Phosphate	mg/L		< 0.5		< 0.5
Sulfate	mg/L	263	–	1200	698
DOC	mg/L	1.1	–	7.3	2.2

*calculated from Si

The majority of the samples show high concentrations of sodium and chloride, which classifies the sampled ground waters as brackish. The analyzed water samples range from low salinity brackish water with a TDS just over 500 mg/L (minimum sample in Palestine) to high salinity brackish waters with a TDS above 5,000 mg/L (maximum sample in Jordan, TDS ~ 7,000 mg/L). In average the sampled waters are of medium salinity with the samples from the Palestinian areas (TDS ~2,100 mg/L) being of lower salinity than the samples collected in Jordan (average TDS ~ 3750 mg/L).

Table 3: Summary of the analysis of water samples collected in Uja and Jericho, West Bank

N = 55 Parameter		Raw Water (West Bank) (Min - Max)			(Mean)
pH (25°C)		7.5	–	8.5	8.0
El. conductivity (25°C)	mS/cm	0.92	–	8.08	3.57
Barium	mg/L	0.03	–	0.35	0.10
Boron	mg/L	0.30	–	3.49	0.97
Calcium	mg/L	19	–	568	106
Iron	mg/L		< 0.025		< 0.025
Potassium	mg/L	9.8	–	249	64.5
Magnesium	mg/L	46	–	218	95
Sodium	mg/L	74	–	3018	451
Silica*	mg/L	6.8	–	28.5	18.6
Strontium	mg/L	0.3	–	14.7	3.0
Chloride	mg/L	114	–	5650	903
Bromide	mg/L	0.8	–	64.2	11.1
Nitrate	mg/L	0.5	–	86.0	24.4
Sulfate	mg/L	41	–	1225	205
TOC	mg/L	0	–	5.7	0.3

*calculated from Si

Noticeable are elevated levels of nitrate in many samples, which may be due to infiltration of fertilizers or wastewater into the aquifer. DOC values are elevated as well considering the samples are from a groundwater source. The DOC values are closer to the range of surface water. However, there is some uncertainty with the accuracy of the DOC value of the samples as most of them have undergone a suboptimum transport and storage process. Levels of iron and manganese are low in the samples but could actually be higher as these metals are oxidized upon contact with air. In most cases, it was not possible to prevent air contact prior to sample collection.

There are other parameters, compounds and elements which influence membrane system design (e.g. pre-treatment) and fouling propensity. The most prominent being suspended particulate matter, which can be assessed via turbidity measurements or identification of the SDI, which is a common parameter to assess the colloidal fouling propensity of a source water. Particulate matter can strongly affect pre-treatment design and operation as well as fouling in membrane systems. The pre-treatment should ensure, as a minimum requirement for RO-systems, turbidity levels of less than 1 NTU and an SDI of less than 5. Membrane manufacturers recommend an SDI of less than 3.

Secondly, brackish ground waters can contain gases, especially hydrogen sulfide at concentrations greater than 0.1 mg/L. This gas can adversely affect RO-system performance by reacting with metals to form metallic sulfides or by forming sulfur when in contact with air. Metallic sulfides cannot be completely retained by cartridge filters, which means that they accumulate in the feed channel and on the membranes. If hydrogen sulfide is present in the well water, it is best to operate the complete system under anaerobic conditions, meaning that no air is introduced to the system at any point. The gas can then be stripped from the permeate side as a posttreatment step.

Thirdly, the well water may contain high concentrations of iron and manganese, which cause fouling and make membranes more susceptible to oxidation damage. When in contact with air, iron and manganese oxides are formed which are insoluble. That represents also the easiest and most common way to remove iron and manganese in pre-treatment (see 3.2.2 Aeration). However, this strategy cannot be applied if the well water also contains hydrogen sulfide as metallic sulfides cannot be retained by the subsequent filtration step and will enter the membrane section.

SDI – Silt Density Index (ASTM D4189)

The SDI is determined by filtering a water sample through a 0.45-micrometer filter at a constant pressure of 2.1 bar (30 psi). The time it takes to collect 500 mL of filtrate is measured initially (t_0 in sec) and again after 15 min (t_{15} in sec). The SDI can then be calculated:

$$\mathrm{SDI}_{15} = \left(1 - {}^{\mathrm{t}_0}\!/_{\mathrm{t}_{15}}\right) \cdot {}^{100}\!/_{\mathrm{T}_{15}}$$

T_{15} is the total elapsed time in sec; 15 minutes (900 s) are most common.

It gives the percentage drop in flow rate per minute due to the plugging of the filter. SDI at <3 is recommended to minimize fouling.

The water analysis shows that fouling is most likely caused by scaling of barium sulfate, calcium fluoride, calcium carbonate and to a lesser degree by calcium sulfate, strontium sulfate and silica. An antiscalant is essential in treating these waters. The high water temperatures in addition to elevated levels of DOC also support biofouling. A membrane autopsy of old elements upon replacement is helpful to determine the primary causes of fouling of a RO-system.

2.2. BRACKISH WATER DESALINATION IN JORDAN

In the Lower Jordan Rift Valley of Jordan, farmers have already begun using reverse osmosis desalination units privately about 20 years ago. Since then a local market has established with Jordan based companies supplying RO-units. Rather than importing complete systems, local companies design the systems, import parts and do the assembly and commission. Membrane desalination technology is also operated privately and by the government for drinking water supply from small scale all the way to large scale.

Figure 2: Brackish water RO-System for drinking water supply in Jerash, Jordan, operated by the Jordanian water authorities (photo: Oliver Jung)

In 2016, about 50 RO-units were run on farms in the Jordan Valley. Ten farms, which operate desalination units, have been visited during summer. All were planting banana amongst other crops except for one, which specialized on herbs. A complete data set for water analysis was available for six of them. The water analysis was done at the EBI in Karlsruhe, Germany. The Department of Agricultural Economics and Agribusiness Management at the University of Jordan provided additional data on capacity, flow values and salinity for 46 units in the region (data collected by a survey).

Most RO-Units currently installed are very similar in terms of capacity and layout. The majority of systems is designed to process less than 50 m³/h with a product capacity of less than 30 m³/h. Table 4 gives a summary of the collected data from the University of Jordan.

Table 4: Basic system parameters of RO-units in Jordan (as of 2016)

Desalination in Jordan N = 46		Min	–	Max	Mean
Capacity	m³/h	15	–	100	42
Product Capacity	m³/h	10	–	70	27
Recovery	%	40	–	78	64
Feed Salinity (TDS)	mg/L	1300	–	7000	3150
Brine Salinity (TDS)	mg/L	3000	–	18000	7950
Permeate Salinity (TDS)	mg/L	23	–	800	195

Feed salinity ranges from medium to high with the majority of plants (80%) running with a feed salinity below 4,000 mg/L. The average recovery of 64% is considered low for brackish water desalination. According to the survey, half of the plants operate at a recovery at and below 60%. The low recovery confirms that most of the plants are single-stage as was seen during the visit. A simple single-stage system has lower engineering design requirements and thus may have the lowest initial capital costs, which may be the prime reason for its large market share. The plants of higher recovery are most certainly two-stage systems. Thirteen plants were reported to operate at a recovery ≥70%, which represents 25% of the plants in the survey.

Figure 3: Typical RO-unit on a farm in Jordan (photo: Oliver Jung)

Generally, a recovery of 70% to 85% can be expected with brackish water desalination with the limiting factor being usually scaling. Antiscalant manufacturers can provide customers with an estimation of maximum recovery given a complete water analysis. An example simulation for a two-stage system with a system recovery of 75%, permeate production of 30 m³/h and a feed salinity of about 4,000 mg/L using feed water data from one of the farms is given in appendix 8.2. Higher water temperatures also reduce maximum recovery of a given system.

Table 5 shows the mean values for the six farms of which a complete data set for water analysis was available. The data shows a very high salinity (conductivity) for the permeate which indicates poor performance and membrane failure. Indeed, one of the sampled systems was severely corrupted and could not reduce salinity to acceptable levels. One more system was performing poorly with a product conductivity of 1 mS/cm (TDS ~600 mg/L) whilst the other four systems performed acceptable with a product conductivity of about 0.5 mS/cm (TDS ~300 mg/L).

Table 5: Water analysis from feed, permeate and brine of six RO-units on farms in Jordan

N = 6 Parameter		Feed (Mean)	Permeate (Mean)	Brine (Mean)
pH (30°C)		6.8	6.1	7.1
El. conductivity (25°C)	mS/cm	7.14	1.49	13.75
Barium	mg/L	0.05	0.02	0.09
Boron	mg/L	1.37	1.06	1.65
Calcium	mg/L	292	47	562
Iron	mg/L	0.02	< 0.01	0.01
Potassium	mg/L	85	19	169
Magnesium	mg/L	230	39.4	485
Manganese	mg/L	0.007	0.003	0.008
Sodium	mg/L	848	199	1631
Silica*	mg/L	24.8	4.3	61.9
Strontium	mg/L	5.7	1.0	12.8
Fluoride	mg/L	1	0.3	2.4
Chloride	mg/L	1960	439	3995
Nitrite	mg/L	5.9	1.5	8.3
Bromide	mg/L	24.6	5.1	45.1
Nitrate	mg/L	55	16	281
Phosphate	mg/L	< 0.5	< 0.5	1
Sulfate	mg/L	731	131	1347
DOC	mg/L	2.7	-	5.9

*calculated from Si

Figure 4: Product water storage and mixing pond on a private farm in Jordan (photo: Oliver Jung)

The permeate is typically blended with raw water in an open product pond which is located in close proximity to the station. This water is then used for irrigation. Some farmers also store excess permeate in a tank for the purpose of selling or distribution. In that case, the water is transported with a truck. The brine is also discharged in proximity to the station either on the ground, in a nearby channel or in a small pond.

Figure 5: Brine discharge in a small pond (left) and on land (right) next to a RO-unit in Jordan (photos: Oliver Jung)

The already large number of farmers applying brackish water desalination in Jordan demonstrates the principal economic feasibility of the implementation of RO-systems for brackish water desalination in the Jordan Valley. The current practice shows that farmers rely on simple systems of low overall complexity, which they are able to operate successfully although in some cases poor performance is being tolerated. Brine disposal is an issue, as there seems to be no option for responsible discharge in place. Improvements can be made regarding the recovery. Product storage in rather shallow open ponds is also not an ideal solution as the pond is subject to pollution from the environment and product loss due to evaporation (evaporation loss can be equal to the product output of one full day of operation) and leakage.

3. BRACKISH WATER DESALINATION

RO/NF membrane desalination technology is a state of the art water treatment technology [6]. When compared to traditional water treatment technologies however, it is still more expensive though research over the past decades has led to considerable improvements. Its key advantage is the ability to remove salts, e.g. sodium chloride, which most traditional treatment technologies are not capable of. Compared to other desalting technologies such as distillation and electro dialysis, RO/NF membrane desalination is superior in energy demand and cost efficiency [7]. For brackish water desalination, RO/NF membrane systems particularly are generally the most cost effective treatment solution, both in capital and operating cost. Therefore, RO/NF membrane systems are the prime choice to utilize a brackish water source for the complementation of traditional freshwater sources and for raising a regions total water stock.

In the LJRV, a region with severe water scarcity and decreasing freshwater availability, desalination provides value to local farmers. Research conducted by the University of Jordan showed that the production cost of freshwater from brackish groundwater in the region is less than the expected return from value crops when used for irrigation purposes. Such favorable economics are the prime reason for Jordan farmers to continue implementing membrane desalination technology. Figure 6 shows a typical layout of a brackish water desalination RO-unit on a Jordan farm with a permeate production capacity of about 20 m^3/h.

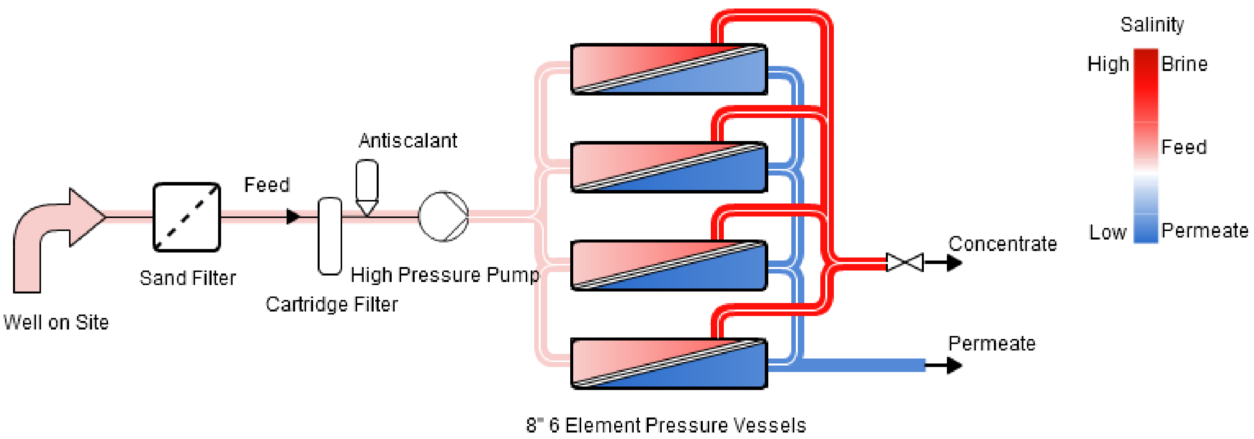


Figure 6: General layout of a typical RO-unit on a farm in Jordan

A RO/NF membrane treatment plant consists of three sections; (1) the pretreatment section, (2) the membrane section and (3) the posttreatment section (see Figure 7).

(1) The pretreatment section receives the raw water and processes it to a suitable water quality for the membrane section. The most common pretreatment tasks are the removal of suspended solids, pH adjustment, disinfection, the removal of any chemicals, which can damage the membranes (e.g. chlorine), and oxidation.

(2) The membrane section houses the RO/NF membranes. It is the high-pressure section of the system. Its main task is the removal of salts and residual organics. The membrane section produces a concentrate waste (brine) which has to be disposed.

(3) The posttreatment section is processing the corrosive permeate into the desired product water quality. This is usually done by adding chemicals (e.g. fertilizer) and/or blending with raw water or another water source.

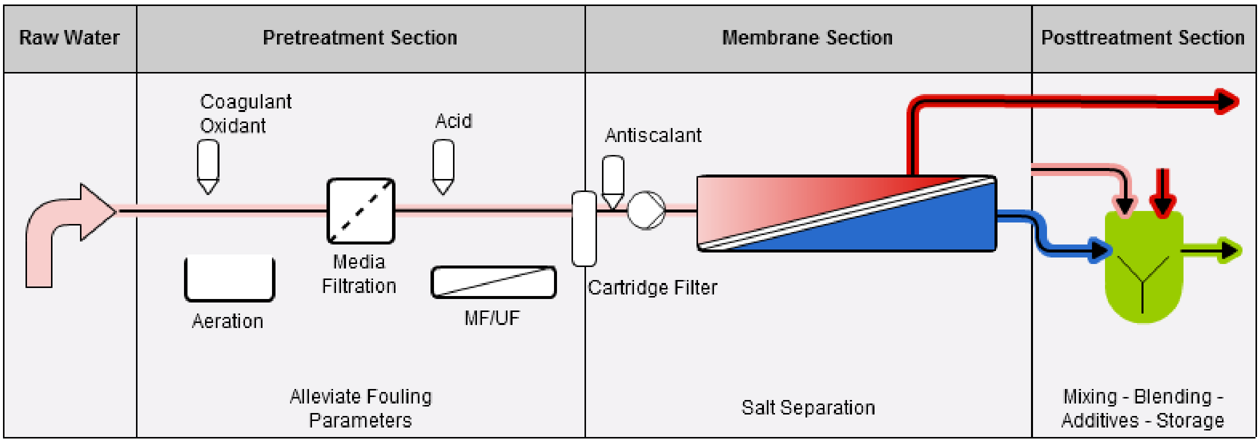


Figure 7: System Design of a RO/NF treatment plant

3.1. DESIGN AND OPERATIONAL CONSIDERATIONS – THE FOULING PROBLEM AND BASIC STRATEGIES

A membrane filtration process run over time will inevitably experience a loss of flux, i.e. product output, and/or an increase of energy consumption, i.e. an increase of feed pressure. The reason for this decrease in efficiency is fouling. Mitigating fouling is the most important design aspect of a membrane treatment plant behind the general layout [8]. The primary aim of the system design is operational stability with maximum membrane lifetime, i.e. stable recovery rate, stable rejection and stable feed pressure, while minimizing operational costs. These goals can only be reached by appropriately addressing the fouling phenomenon.

In brackish water treatment, there are three main causes for fouling, i.e. scaling, biofouling and particles. All of these foulants do agglomerate on the pressure side of the membrane and negatively affect membrane performance.

Particles can clog and damage membranes by means of abrasion and should always be removed completely before the RO or NF module. In most cases, this can be done rather easily by filtering through sand and cartridge filters.

Biofouling is usually a minor problem with groundwater but can be a significant problem with surface water because of the generally higher organic carbon load in these waters. Biofouling can also be very difficult to clean without intense use of cleaning chemicals. Reducing the concentration of bacteria and reducing TOC and DOC, e.g. using coagulation-flocculation, can decrease the biofouling potential of the feed water. At DOC levels around 0.5 mg/L, biofouling is not expected to be major whereas at levels over 2 mg/L biofouling is likely. High water temperatures also promote biofouling.

Scaling is the precipitation of minerals on the membrane surface. It is caused by concentrating the feed water to the point where salt is no longer stable in solution (oversaturation). This effect is inevitable and generally limits the maximum applicable recovery in brackish water treatment, usually 70% to 90%. By adding antiscalant to the feed water, salt can be retained in solution longer, i.e. ion concentration can be increased before salt precipitates, which reduces scaling and allows for higher recovery.

In order to alleviate fouling pretreatment is generally necessary and a good design can reduce membrane fouling considerably. An overall successful system design is based on a feed water analysis to assess the risks of each type of fouling. The next step is to design a series of pretreatment steps to minimize fouling. The design of the membrane system is then based on the pretreatment. Unsuccessful pretreatment results in increased operational cost, shorter membrane lifetime, reduced recovery and less system integrity. The following chapter addresses the most common pretreatment options.

3.2. PRETREATMENT

Pretreatment has a critical influence on desalination plant performance, maintenance and operation. A badly designed or inadequate pretreatment may increase fouling problems, cleaning cycles and membrane replacement cycles significantly. The proper pretreatment design is largely dependent on the raw water composition and its source. A complete water analysis is mandatory and the importance of a good analysis with reliable data for the design of the pretreatment section cannot be overemphasized. The pretreatment may also affect the posttreatment steps [7-13].

The ideal pretreatment is always a compromise between economic considerations and fouling considerations. Therefore, the pretreatment has to be designed individually for every new application. The following chapters present different pretreatment systems with a short explanation of their function and area of application.

The prevalent brackish water source in the Lower Jordan Valley is well water with medium to high salinity and medium to high organic load. Generally, well water is a very consistent feed water source with relatively low fouling potential. Pretreatment may only require removal of particles, pH adjustment and antiscalant dosing. However, the water analysis of brackish groundwater in the Jordan Valley suggests that the groundwater is influenced by surface and/or wastewaters, which lead to seasonal changes and higher organic and chemical load. In addition, groundwater often is in a reduced state and may contain harmful levels of dissolved iron and manganese, which would have to be oxidized for removal. Additional pretreatment steps may be appropriate, e.g. oxidation/aeration and coagulation-flocculation.

Further considerations can also influence the extent of pretreatment required for a desired application. A very complete pretreatment section, which reduces the fouling potential of the feed water to a minimum, e.g. using oxidation, media filtration, coagulation-flocculation and ultrafiltration, is high on investment cost and more challenging to operate. In turn the membrane system can be operated with high permeate flux and almost no cleaning will be required. Lifetime of membrane is maximized and the number of membrane elements is minimal. In comparison, a pretreatment section leaving a higher fouling potential of the feed water to the membrane system would require more membrane elements, more frequent cleaning and/or cleaning with more abrasive chemicals and more maintenance. Additionally membranes would have to be replaced more frequently.

3.2.1. DEPTH FILTRATION

Depth filtration (also media filtration) for the removal of suspended and colloidal particles is an extremely common pretreatment technology. The suspended matter is removed by filtering the feed water through a bed of grains (e.g. silica sand, anthracite coal). The particles adsorb and deposit on the granular media. Two types of filters are common, gravity and pressure filters, which differ in filtration rate, size and operating pressure. The filters can be regenerated by backwashing during which the adsorbed and deposited matter is removed and discharged. This is done periodically whenever the differential pressure passes a certain threshold, e.g. 0.3 to 0.6 bar. The effective grain size of sand filter media is in the range of 0.35 to 0.5 mm. The typical filtration velocity for a rapid sand filter is between 3 and 20 m/h.

The effectiveness of media filters can be assessed by determining turbidity and SDI before and after the filter (with the SDI being the more important parameter). Media filtration without coagulation-flocculation should be able to reduce the SDI to less than 5 and turbidity to less than 0.1 NTU.

Figure 8: Sand filter of a RO treatment plant on a farm in Jordan (photo: Oliver Jung)

3.2.2. OXIDATION (AERATION)

Many brackish ground waters are in a reduced state meaning that not all elements are fully oxidized, also referred to as anoxic waters as no oxygen is present. When those waters are pumped to the surface, some constituents are oxidized which can lead to severe fouling problems within the membrane system. Most common is the presence of divalent iron and manganese, which in their respective oxidized state form insoluble salts, which precipitate.

The simplest way of handling anoxic waters is to pass them through an aeration unit before the media filtration step. Air is used for oxidation and the precipitate is removed by the subsequent filter. An aeration unit can be an open tank where the residence time is long enough for a complete oxidation. The effectiveness is increased the greater the contact area of the two phases (water and air). The contact area can be increased by bubbling air through the tank from the bottom or flowing the water over a mixing plate. Oxidizing agents such as chlorine or ozone can also be added.

3.2.3. COAGULATION-FLOCCULATION

Coagulation-flocculation is a well-established process in general drinking water treatment. This process can very effectively remove suspended matter, including organic carbon and increases the effectiveness of the subsequent filtration step. Ferric chloride, ferric sulfate and aluminum hydroxide are common coagulants. However, residual aluminum is prone to cause fouling (scaling) problems in the membrane section and therefore aluminum-based coagulants are not recommended.

Coagulants are of very low solubility and immediately precipitate while also destabilizing the negative surface charge of particles and colloidal matter present in most raw waters. The colloids and suspended particles agglomerate and form flocs, which further grow. These flocs can be easily removed by sedimentation or subsequent filtration. The rapid dispersion and mixing of the coagulant is crucial. The coagulant should for example be injected before a static mixer or directly in front of a pump. Correct dosing is also important and has to be determined case by case. Jar tests are very common for this purpose and can be conducted on site. Incorrect dosing may result in insufficient removal or clogging of filters and membranes. Residual coagulant can also react with antiscalant, which may then precipitate on the membranes causing heavy fouling which is difficult to clean.

Certain polymers can increase the effectiveness of coagulation-flocculation and are often added. However, as with antiscalants, the polymers itself may cause organic fouling and might be used as a food source by microorganisms and thus increase the risk of biofouling.

3.2.4. MICROFILTRATION/ULTRAFILTRATION

Microfiltration (MF) and ultrafiltration (UF) almost completely remove particulate matter as well as bacteria, algae and other microorganisms from the feed water. When combined with flocculation, dissolved organic carbon, which generally is not retained by MF/UF, can be reduced as well.

The integration of a MF/UF-System in the pre-treatment is comparatively capital intensive but provides the highest quality feed water for the membrane section. A MF/UF-System also requires additional expertise from the operator as well as a more sophisticated system control setup. A cleaning protocol consisting of backwashing as well as chemical cleaning cycles is necessary for stable operation. For these reasons, MF/UF-Systems for pre-treatment are not generally recommended for non-automated systems.

Because of its high quality, ultrafiltration pretreatment is becoming increasingly popular for brackish water systems.

3.2.5. IN-LINE CARTRIDGE FILTRATION

Cartridge filter are most commonly applied with pore sizes of 5 to 10 µm. Cartridge filter require little expertise for operation. Cartridges are simply replaced after a certain time (e.g. 3 months) or after they are clogged which is indicated by the limit for the maximum pressure drop allowed across the filter. However, cartridges are rather expensive and exclusive usage of cartridge filters for pretreatment would be inefficient in most cases. A preceding sand filter, which can remove a large part of the suspended matter, is likely to be more cost effective.

A 5 µm cartridge filter at the end of the line before the high-pressure pump is a standard safety devise to prevent any damage to the pump and membranes caused by particles. Although the most pretreatment set-ups already contain a filtration step, particles can also originate from the set-up itself (e.g. corrosion) or be introduced or formed by chemical addition outside the water source (e.g. antiscalant) which are

Figure 9: 5 µm filter cartridge and cartridge filter of a RO treatment plant in Jordan (photos: Oliver Jung)

not covered by the pretreatment filtration. The cartridge filter therefore acts as a last barrier; it can also be considered a part of the membrane section. The SDI before and after the filter at the end of the line should not be significantly different (less than 1 unit [8]). A high difference points towards problems in the pretreatment.

Cartridges should be replaced before the pressure drop across the filter increased to the manufacturers limit and at least every 3 months to prevent biofouling. A rapid increase of the pressure drop or necessary replacement before 3 months of operation indicates problems with the pretreatment section. A high-pressure drop increases the risk of a breakthrough of particles and subsequent premature failure of the membrane system.

Figure 10: Biofouling in a filter cartridge (photos: Florencia Saravia)

3.3. NOTES ON SCALING

Scaling is the precipitation of salts onto the membrane surface, which leads to a reduction of flux or respectively to an increase of feed pressure. The scaling phenomenon is governed by the feed water chemistry and the system recovery. For example, if system recovery is 50%, then the concentration of salts in the brine is double the concentration of salts in the feed. In case solubility limits of certain sparingly soluble salts are exceeded after doubling concentration, precipitation (scaling) occurs. Another phenomenon, which adds to the rising concentration of the feed water, is concentration polarization. The polarization occurs near the membrane surface and is caused by the rejection of ions by the membrane whereas water is transported through the membrane to the permeate side. This means that the salt concentration at the membrane surface is even higher than the brine concentration (bulk concentration) and precipitation is more likely. Therefore, scaling occurs most prominently at the end of the last elements in line and at those elements with the highest flux. Also, whenever recovery of a plant is increased, so is the risk of scaling.

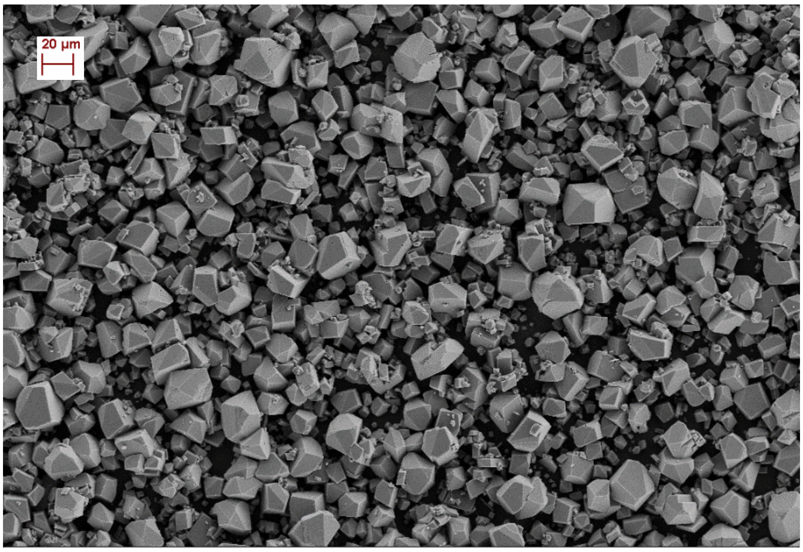


Figure 11: SEM image of scaling on a brackish water RO membrane (imaged at KIT)

The most common sparingly soluble salts present in brackish ground waters are calcium carbonate, calcium sulfate and silica. Other notable scaling risks are calcium fluoride, barium sulfate, strontium sulfate and calcium phosphate. Ferric and manganese salts may also lead to extensive scaling if they were not oxidized and removed prior to filtration.

Most scaling, i.e. carbonate, sulfate and calcium fluoride scaling can be controlled by adding antiscalants, which act as scale inhibitors. Carbonate scaling can also be controlled adjusting the pH by adding acid. The risk of carbonate scaling is usually expressed by the LSI. Ferric and manganese scaling is best prevented by oxidation and filtration in pretreatment. Calcium phosphate scaling is rather uncommon with natural water sources. However, if the raw water source is subject to infiltrating wastewater or fertilizers it may be an issue. If scaling cannot be controlled, the system recovery has to be reduced or another raw water source has to be utilized.

Common antiscalants are sodium hexametaphosphate (SHMP), organophosphonates and polyacrylates. The latter are more expensive but also more effective and stable scale inhibitors than SHMP. SHMP is generally not recommended as it may be subject to hydrolysis in the dosing feed tank. Hydrolysis decreases the effectiveness of SHMP and creates a calcium phosphate scaling risk in itself. The exact composition of an antiscalant mix is generally known only to the antiscalant manufacturer.

LSI – Langelier Saturation Index

Assesses the tendency of calcium carbonate scale formation.

$$\mathrm{LSI} = \mathrm{pH} - \mathrm{pH_s}$$

pH – actual pH

pH_s – pH value if the solution were saturated with calcium carbonate. It is the sum of the calcium concentration, alkalinity and a constant accounting for TDS and temperature.

LSI greater 0 means that calcium carbonate precipitates. The addition of Antiscalant can control values up to a LSI of 3.

A negative LSI means that the water is aggressive and dissolves calcium carbonate.

The risk of scaling can be calculated from the raw water analysis and/or the water analysis after pre-treatment. These calculations should be done by the supplier of the antiscalant and the antiscalant should then be dosed according to the manufacturers' recommendations. Antiscalants of different manufacturers should not be mixed to prevent any cross-reactions of scale inhibitors, which may lead to irreversible fouling. Some antiscalant manufacturers also provide software to calculate the dosing requirements for a given feed water, which can be used to calculate the maximum system recovery. Because the dosing of antiscalant is generally based on the concentration of antiscalant in the brine, the total amount of antiscalant necessary decreases with increasing recovery since with increasing recovery less brine is produced. Even with less antiscalant added to the feed, the concentration in the brine will be higher than with lower recovery (brine is more concentrated at higher recovery, so a higher concentration of antiscalant is required). This means that a treatment plant with higher recovery requires less antiscalant absolute than a plant of the same size with lower recovery. An example is given in Appendix 8.3.[8, 13-16]

3.4. NOTES ON BIOFOULING

Microorganisms are ubiquitous in natural waters. They can be regarded as suspended matter and thus be removed by filtration. Due to their small size (about 1 µm), only ultrafiltration is sure to completely remove microorganisms. However, the great fouling potential of microorganism is not rooted in their size but in their ability to reproduce and form biofilms. A membrane system poses favorable conditions for microorganisms for several reasons: nutrients are supplied continuously during operation through the feed water, membranes provide a large surface for the biofilm to grow and spacers allow for additional attachment area and protection from shear stress. Once biofilm fouling is present, membrane flux is reduced and differential pressure is increased. Removal of biofilm is rather difficult as microorganisms develop it as a means of protection. A biofilm can resist biocidal chemicals and shear forces. Even if microorganisms are killed, a failure in completely removing all the dead matter usually results in rapid regrowth. Removal of biofilm therefore has to be rigorous. Cleaning procedures are also much more effective on a young biofilm than on an aged one. Altogether, it means that biofilm fouling is best dealt with using preventive methods to keep microorganisms from establishing a biofilm for as long as possible.

An effective approach is the limitation or removal from nutrients, such as readily degradable organic carbon. A good pretreatment system can remove most of the DOC but not all. For example, an UF-System can remove microorganisms and viruses but does by itself not remove the small fractions of dissolved organic carbon. Thus, biofouling may still occur in the membrane section.

Figure 12: biofilm on a spiral wound element inlet (left); biofilm on a NF membrane (middle); membrane with some biofilm scraped off (right). (Photos: Florencia Saravia)

Another approach is the inactivation of microorganisms by oxidation, e.g. chlorination or UV-irradiation. The most common RO/NF membranes are not resistant to chlorine, which means that it has to be removed again prior to the membrane section. Chlorination of the feed water has long been a standard. However, problems with biofouling were still common. This may be explained by a better nutrient availability subsequent to the chlorination step. Through chlorine, organic carbon compounds are broken down to fragments, which are more readily biodegradable than the original compounds. Thus, biological growth although completely stopped during chlorination, can recommence more rapidly in the membrane section. It is also possible that readily biodegradable compounds are introduced by the set-up (e.g. through antiscalant addition).

It is impossible to completely remove or inactivate all microorganisms in a standard membrane system. However, regular servicing such as regular replacement of cartridges in filters or regular backwashing of filtration systems as well as the prevention of leakages are considered basic requirements to minimize biofouling. Type and dosing of any chemicals added during pretreatment should also be considered as they may be harmful to the membranes or serve as nutrients for microorganisms itself, e.g. antiscalant [17].

3.5. POSTTREATMENT

Desalinated water is corrosive and must generally be stabilized before it is introduced into a distribution system. Chemicals are mostly added to the permeate for the purpose of preventing corrosion and ensuring compatibility with other water sources. Depending on the desired product characteristics, chemical addition such as fertilizers for addition of nutrients or sodium hypochlorite for disinfection may also be necessary to make the product suitable for application. In case hydrogen sulfide gas is present in the raw water it is generally stripped from the permeate as a posttreatment step.

3.6. BRINE MANAGEMENT

The management of the saline by-product of RO/NF membrane processes is one of the most important environmental issues of inland brackish water desalination. Two important parameters need to be considered first when assessing brine management, salinity and quantity. Both depend on the recovery. Salinity is also largely influenced by the feed water chemistry. Brackish water desalination typically operates at a recovery between 60% and 85%. This means that 15 to 40% of the total treated brackish water accounts as concentrate waste. It also means that the brine is by a factor of 2.5 to 6.7 more concentrated than the feed water. At higher recovery, the salinity can reach values close to typical seawater salinity. In addition to the salts already present in the raw water, brine also contains the chemicals added in the treatment process, i.e. antiscalant, cleaning chemicals etc.

Brine management is usually a major cost consideration factor for inland brackish water desalination in countries which enforce regulations for waste disposal (e.g. the EU) and a readily available discharge site (e.g. the sea) is often not available. Brine quantity, brine concentration, the regulatory framework and local geology are the main parameters to determine the best brine management strategy, which in most cases is likely to be the most cost efficient. A number of management options can be considered which are shown in Figure 13 [7, 13, 18, 19].

Land application with no preceding brine treatment is easy to implement with low initial cost requirements. However, it is also the least sustainable solution. Adverse environmental effects due to brine discharge are widely recognized [20]. Soil and groundwater are most affected by brine. Increasing groundwater salinity and decreasing soil value and soil productivity are possible results from land application. These adverse environmental effects accumulate to what can be referred to as “hidden costs”. Increasing groundwater salinity makes future desalination more expensive and a reduction of crop yield results in diminished returns. It is conceivable that these “hidden costs” amount to making land application the most cost intensive brine management solution. The actual environmental impact of land application is difficult to specify and largely dependent on quantity, concentrations and geological conditions.

Transport of the brine from the area of application to suitable disposal sites (e.g. coastal regions) can be a low cost solution if the distance is not too large and the brine does not need to be pumped to higher altitudes. This way the brine can be potentially discharged to sea or diluted with other wastewater sources. The only investment in that case would be piping which prevents leakage and possibly a distribution pump. The environmental impact then effects another area where it would be of lesser concern. The close proximity of the highly saline Dead Sea downstream to the Lower Jordan Valley possibly makes this option the most cost effective and preferable solution for brine management in Jordan and in the Palestinian territories.

Solar evaporation is an option mostly restricted to semi-arid and arid regions. It requires an evaporation pond and a high evaporation capacity. The pond should be shallow with a large surface area. The residual salt can be removed and discharged as solid waste. Evaporation ponds require a large land area and have to be fitted with an impermeable lining to prevent leakage into the underlying groundwater aquifer and soil. This lining constitutes most of the cost of solar evaporation. Once constructed an evaporation pond requires very little maintenance.

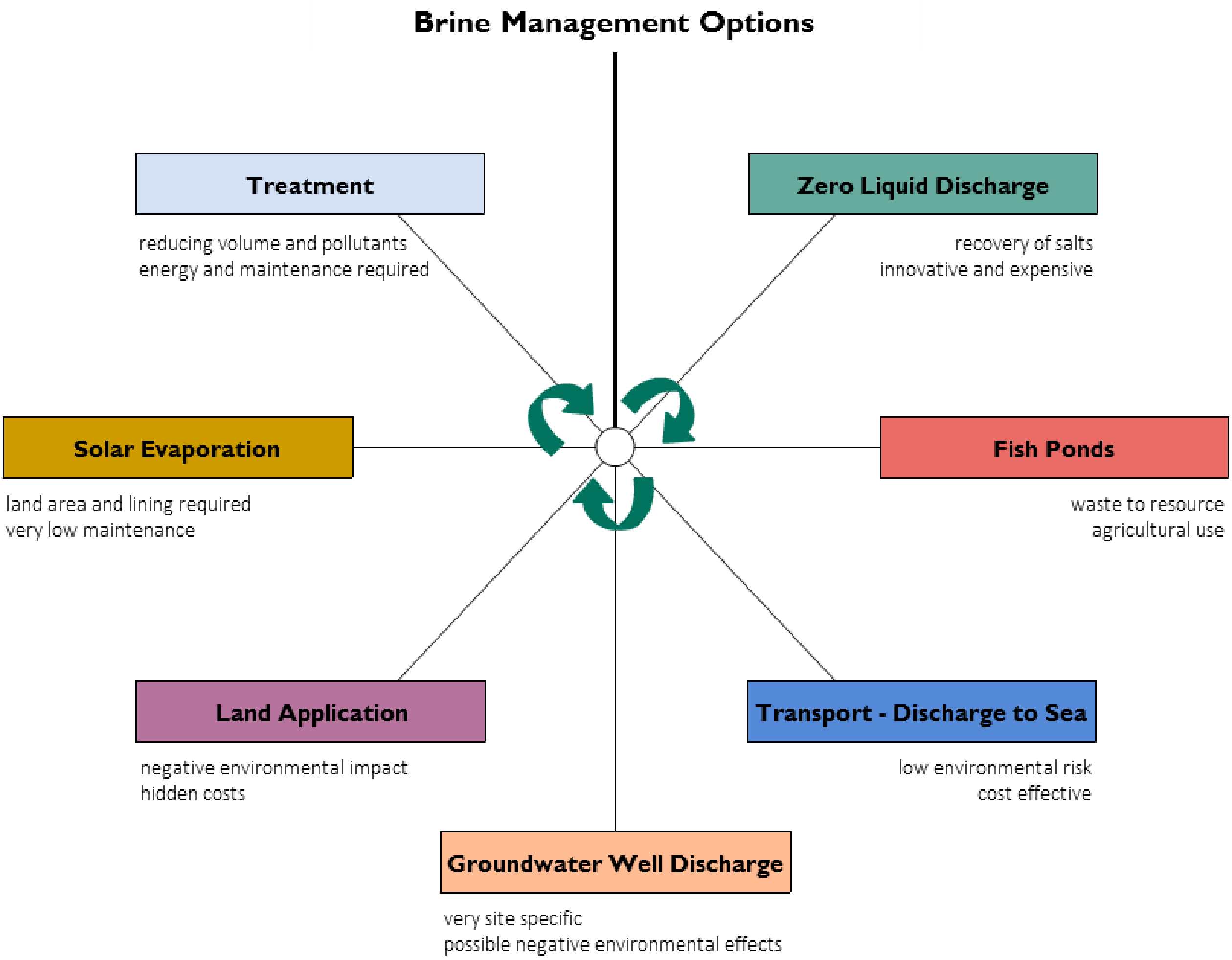


Figure 13: Options for brine treatment and disposal

Groundwater well discharge describes the injection of brine into groundwater. The groundwater should be of the same or higher salinity then the brine. It should also be certain that the injection does not affect other groundwater aquifers, particularly if those aquifers are used for drinking water supply.

Fishponds are an example of trying to turn a waste into an economic resource. With a sufficient amount of brine of stable and suitable quality, it could be used for purposes such as fish farming for either the seafood industries or maybe even for breeding and export.

The general aim of brine treatment is the reduction of the environmental impact by either reducing the volume and/or reducing the pollutant load. Electro dialysis, forward osmosis or membrane distillation are examples for emerging technologies for this purpose. Those technologies require energy and operational expertise [21-23].

Zero Liquid Discharge aims in reducing brine volume to a minimum and convert the solid waste into a marketable product, i.e. recovering salts. Innovative technologies are being studied to achieve this goal.

Most of these are only being applied at laboratory scale. Promising examples are wind aided intensified evaporation and membrane distillation coupled with crystallization [24].

Table 6: Mean values of the water analysis of the six farms sampled in Jordan in 2016

N = 6 **Parameter**		**Brine** **(Mean)**
pH (30°C)		7.1
El. conductivity (25°C)	mS/cm	13.75
Barium	mg/L	0.09
Boron	mg/L	1.65
Calcium	mg/L	562
Iron	mg/L	0.01
Potassium	mg/L	169
Magnesium	mg/L	485
Manganese	mg/L	0.008
Sodium	mg/L	1631
Silica*	mg/L	61.9
Strontium	mg/L	12.8
Fluoride	mg/L	2.4
Chloride	mg/L	3995
Nitrite	mg/L	8.3
Bromide	mg/L	45.1
Nitrate	mg/L	281
Phosphate	mg/L	1
Sulfate	mg/L	1347
DOC	mg/L	5.9

4. SYSTEM DESIGN

A brackish water treatment plant usually consists of three sections, the pretreatment section, the membrane section and the posttreatment section, (see also chapter 3). The pretreatment section (chapter 3.2) is tasked to reduce the fouling potential of the raw water for the membrane section where the salt separation takes place. Posttreatment is aimed at refining the permeate towards the intended application for the product water. This chapter describes the design and considerations for the membrane section.

The membrane section contains all the high-pressure parts. A number of membrane elements are encased in pressure vessels and arranged in a certain manner with the aim to reach a desired permeate flow and quality. A successful RO/NF system design minimizes feed pressure and membrane costs while maximizing permeate quality, recovery and operational stability. The optimal system design is also dependent on the desired application, location and quality of the pretreatment. It needs to take into account the relative importance of all these parameters. Therefore, the optimal solution can be very case specific.

Permeate quality is mainly dependent on the choice of the membrane, specifically the salt rejection properties of the membrane. An ideal membrane would have high flux as well as high rejection. However, in practice higher rejection generally means lower flux though there can be considerable differences between different types of membranes and membrane manufacturers. Especially nanofiltration membranes due to covering a wider range of molecular weight cutoff can have very different rejection characteristics. Typical brackish water membranes have 95% to 99% rejection of all ions. Typical fluxes are between 20 and 40 l/m^2h depending on the fouling tendency of the feed water.

The desired permeate flow and the membrane flux properties (permeability) dictate the feed pressure required for the system. Feed pressure is increasing with increased permeate flow per unit of active membrane area. At the same time, increasing flux this way also increases fouling as more material is being rejected. In brackish water desalination, the fouling propensity of the feed water usually limits the achievable flux and defines the optimum. This is different from seawater desalination where flux is generally limited by the maximum allowed system pressure (generally about 40 bar). The optimum flux for a brackish water RO/NF system is not a number readily available since it is so dependent on the individual feed water-fouling tendency. Rather, the optimal flux is obtained by experience with a specific water body. Membrane manufacturers have gathered a lot of experiences with different water bodies and their product so that they are able to provide recommendations in their technical manuals. This also again highlights the need for a detailed water analysis of the raw water prior to designing any system. Chapter 8.4 shows an example of information to be collected before starting the design process as recommended in technical manuals [8].

4.1. MEMBRANE CONSIDERATIONS

Membranes are the heart of a NF/RO treatment plant and solely responsible for the reduction of TDS by rejecting ions in solution. Therefore choosing the best membranes for a desired system is critical and depends on the following parameters: rejection properties, feed water quality, average system flux and relative importance of costs. The most common RO/NF membranes are a composite made of a PA-surface layer with a PES-support. They do not tolerate chlorine or any other strong oxidants but are resistant to bacterial decay. The most common arrangement for RO/NF membranes is the spiral wound element, which allows for maximum membrane surface area at minimal total size. In smaller scale desalination, elements with a diameter of 4 and 8-inch (10.2 and 20.3 cm) and a length of 40-inch (101.6 cm) are typical. This allows for a total active membrane area of about 8 m² and about 40 m² respectively.

Brackish water RO membranes have a rejection of greater 95% for all ions. Thus, the remaining TDS in the permeate is low. Nanofiltration membranes reduce the TDS less and they reject divalent ions better than monovalent ions. This means that parameters such as the Na^+/Ca^{2+} ratio are changed considerably. Rejection follows hydrated ion size and ion charge considerations. This means that rejection is generally higher for larger ions. However, rejection with NF membranes can be very case specific. Rejection of certain ions may be diminished or enhanced within a specific system depending on the feed water chemistry. This is rooted in the fact that a charged ion cannot travel through a membrane alone but needs to travel with an ion of a corresponding charge to maintain electrical neutrality in solution (i.e. Gibbs-Donnan effect). Nanofiltration membranes can achieve higher flux at lower feed pressures, thus operate at reduced energy demand compared to RO membranes.

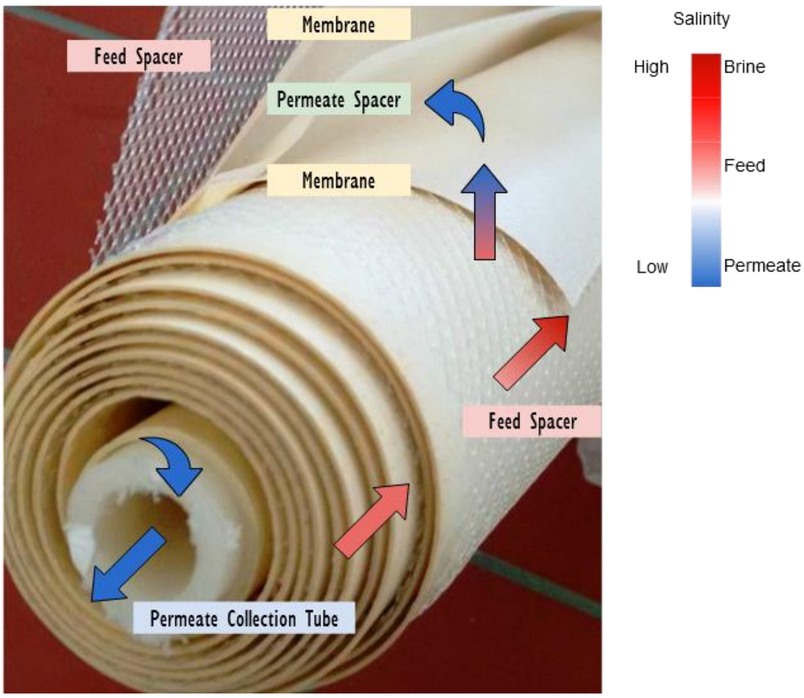


Figure 14: General Layout of a spiral wound RO element (Photo: Harald Horn)

The feed water quality has the greatest influence on the membrane system design. Pretreatment already seeks to reduce the fouling tendency of the water entering the membrane section. The fouling tendency of the pretreated water than greatly influences the achievable flux in the membrane section and can be assessed using the SDI. The membrane system design follows the premise of minimizing fouling rate and preventing mechanical damage. This defines a framework of recommended operating conditions, which are limited by the maximum recovery, the maximum permeate flow rate, the minimum concentrate flow rate and the maximum feed flow rate per element. Membrane manufacturers set those limits as recommended guidelines for their elements derived from experience.

The average system flux dictates the number of elements, which are needed for a desired permeate flow. Poor water quality typically leads to a design with low average flux whereas with good water quality the design can aim for higher flux values. However, lower flux values might still be preferable if the focus lies on minimizing long-term operational costs rather than minimizing capital costs.

4.2. OPERATIONAL DESIGN

RO-systems can be operated in a number of different modes, e.g. continues vs batch, plug flow vs recirculation, single-stage vs multi-stage. Typically the feed water is passed only once through the system (plug flow) and the system is operated continuously where the operating conditions of every element are constant with time, i.e. permeate flow as well as recovery are held constant. Variations in feed water temperature and fouling effects are compensated for by adjusting the feed pressure. Refer to chapter 5.1 for the basic relations of temperature, pressure and flux. Concentrate recirculation and multi-stage design are used to increase recovery.

4.2.1. SINGLE-STAGE SYSTEMS

Single-stage is the most basic design of a membrane system. One or any number of modules are arranged in parallel and connected to a single feed, permeate and concentrate line. All modules have the same inlet and outlet pressure. The standard module is a pressure vessel containing six membrane elements though any number between two and eight is common.

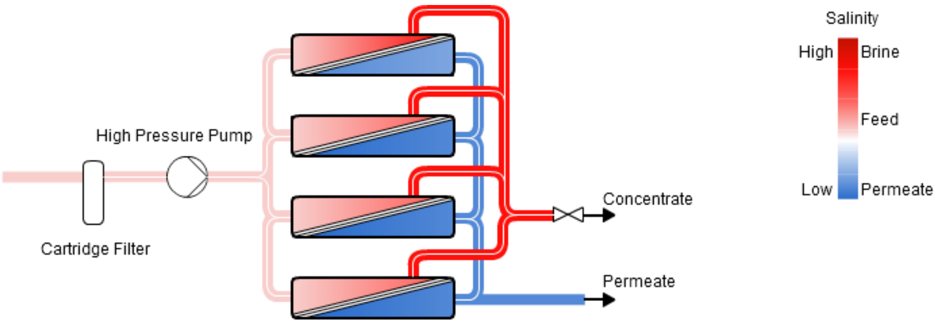


Figure 15: Single stage layout

Single-stage systems operate at a low recovery of 40 to 60% to not exceed the single element recovery limits provided by the manufacturer. In seawater desalination where recovery is limited to around 50% by the maximum system pressure, single stage systems are common. For brackish water desalination, a higher recovery can principally be achieved and is often desired for reasons of efficiency and cost considerations. Low recovery means a loss of valuable water when feed water is scarce. In case the feed water is from a deep well, the energy consumption to supply the raw water to the membrane station is also significant. More raw water needs to be supplied to a system with lower recovery. Furthermore, the pretreatment section also has to be designed for higher feed volume. The advantages of a single stage system are its simplicity and a lesser fouling potential as the brine is not concentrated as much (i.e. less scaling). To increase recovery, an internal concentrate recirculation circuit can be added or the system can be expanded to a multi-stage system.

Table 7: System recovery and number of stages in brackish water desalination. (adapted from DOW Technical Manual [8])

System Recovery (%)	Number of elements in series	Number of stages (6 element vessels)
40 – 60	6	1
70 – 80	12	2
85 – 90	18	3

4.2.2. MULTI-STAGE SYSTEM

In a multi-stage system, the number of elements connected in series is increased. For example, the most common pressure vessel size contains six elements. A single stage system therefore connects six elements in series. In a two-stage system with the same pressure vessels, twelve elements would be connected in series and so on. If shorter pressure vessels were being used, for example containing four elements, then a three-stage system would also connect twelve elements in series.

Passing the feed through more elements in series means that the output volume is lower and the brine more concentrated, hence recovery is increased. In brackish water desalination, a standard two-stage system can increase recovery from maximum 60% of a single-stage system to 80%. With a three-stage system recovery could be further increased up to 90% or even 95%.

Multi-stage systems are arranged in a typical pyramidal structure in which each preceding stage contains more membrane modules than the next one. The ratio of the number of modules of one stage to the next is the staging ratio. The ideal staging ratio is as such each stage operates at the same fraction of the system recovery. In brackish water systems using standard six element vessels, the ideal staging ratio is 2:1, meaning that the first stage contains double the amount of pressure vessels than the second stage. For shorter vessels, containing less elements, the ideal staging ratio is less.

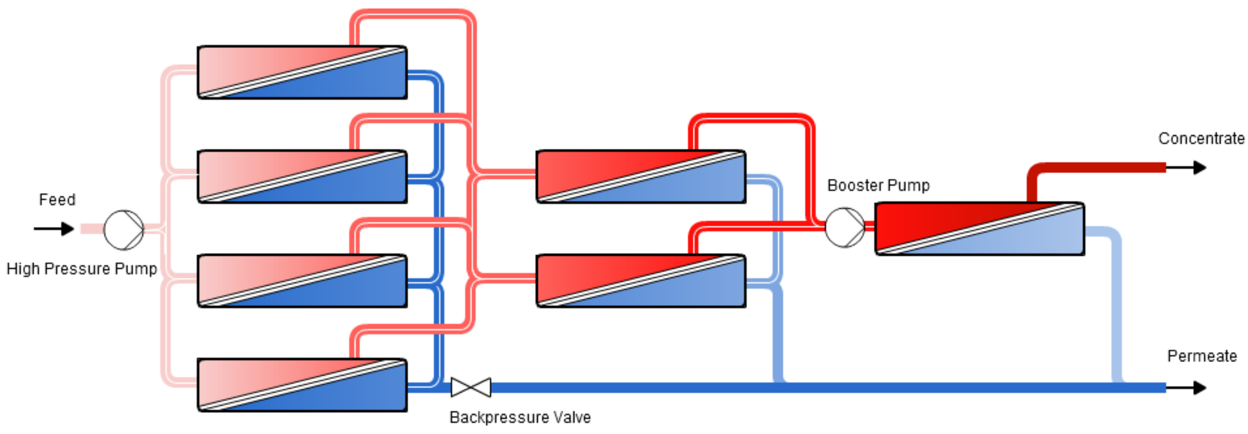


Figure 16: Principal 3-stage layout with either permeate back pressure or feed pressure booster to uniform permeate flow rates

The goal of a membrane system design is to obtain a desired permeate flow with a desired recovery. With those two variables fixed, the feed flow is determined. Therefore, another important aspect of selecting the number of membrane modules per stage is to have optimal flow conditions and comply with the flow limits set by the manufacturer. The pyramidal structure uniforms feed flow by compensating for the permeate removed in each stage. The number of modules in the first stage should be selected as such an optimum feed flow rate is obtained. For an 8-inch element of the first stage, a typical feed flow rate would be about 1.1 m^3/h. The number of modules in the last stage has to be selected as such the limit of the minimum concentrate flow rate of the last elements is met.

A further aspect of multi-stage systems concerns the permeate flow rate. Typically the permeate flow rate of the first elements is greater than the permeate flow rate of the last elements. This is a result of the increasing osmotic pressure of the feed while it passes through the system and gets concentrated to a brine as well as the pressure drop in the feed channel. The permeate flow rate ratio between the first and last elements could potentially become very high for number of reasons, e.g. high system recovery, high water temperature, new membranes. A good system design seeks to balance the permeate flow rate of elements in the different positions to be energy efficient. This can be done for example by boosting the feed pressure between stages or by applying a permeate backpressure to the first stage of a two stage system. Balancing of permeate flow rate may not be necessary for all multi-stage systems.

When working with permeate backpressure, it is very important to have a security valve, which activates in case the high-pressure pump shuts down. The maximum allowed backpressure is 300 mbar above feed pressure. If feed pressure is zero, backpressure has to be no more than 300 mbar above atmospheric pressure or else membranes could be irreversibly damaged.

The advantage of a multi-stage system is a high recovery with a low salt passage, i.e. high reduction of TDS. Multi stage systems are designed for constant recovery and constant feed water composition. Investment cost and energy consumption are low although the design process is more challenging than with a single-stage layout. Multi-stage systems are the most common layout in brackish water treatment.

4.2.3. CONCENTRATE RECIRCULATION

The standard system design is plug flow where the feed volume is passed through the system just once while it is getting concentrated to a brine. With concentrate recirculation a fraction of the brine is directed from the outlet of the module back into the inlet (before the high-pressure pump if no recirculation pump is added) where it mixes with the feed and passes through the module again. This is done to increase the recovery of the system. It also achieves a constant feed flow rate into the module regardless of fouling (as opposed to a multi-stage design). Furthermore, a variance in feed water composition can be adjusted to, in order to keep feed water composition to the module constant. Concentrate recirculation can be incorporated in both a single as well as a multi-stage layout.

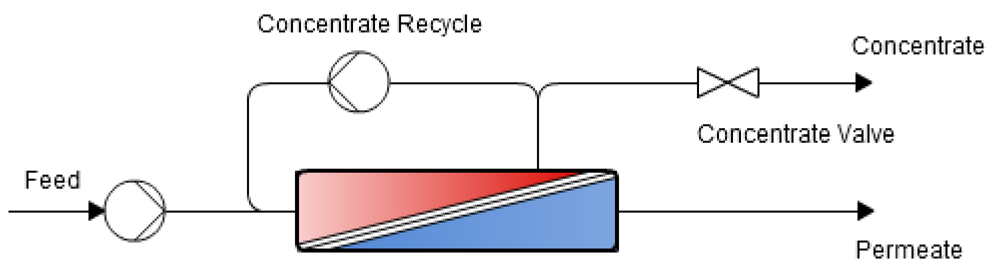


Figure 17: Principle of concentrate recirculation

A recirculation system requires more active membrane area and energy consumption is increased (up to 20%). Furthermore, investment costs are higher since additional pumps have to be added; or in case no pumps are added, the high-pressure pump has to be larger. The permeate quality is decreased as well and regresses further, the larger the fraction of concentrate being recirculated. This means that the reduction in TDS in a system with internal concentrate recirculation is lower than in a system without. However, the reduction in product water quality is compensated for by the increase in product volume. It depends on the specific location and application of a system which factor is of higher value.

Concentrate recirculation is particularly advantageous when water quality and permeate flow are expected to vary rather than being constant at all times. Systems without recirculation can only be operated in between narrow limits of their design values as membrane element flow limits and element recovery limits are quickly exceeded.

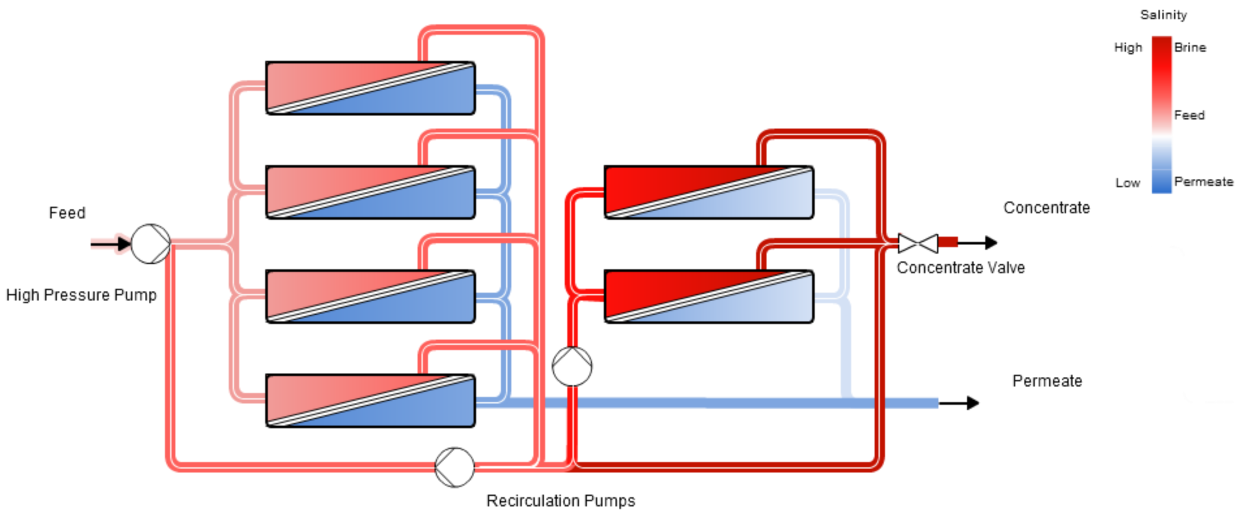


Figure 18: Two-stage layout with concentrate recirculation in both stages

4.2.4. SYSTEM PARTS - CONTROL INSTRUMENTS

A number of parts are essential to any RO-System, i.e. storage tanks, dosing tanks, pipelines, valves and control instruments. Storage tanks should be properly dimensioned and should protect the water from additional contamination. Dead zones in tanks can also lead to accumulation of contaminants, e.g. particles, which may be discharged suddenly and can clog pipelines or filters. This is why dead zones in storage tanks should be avoided by placing inlet and outlet appropriately. Tanks, pipelines and fittings can be of different material, e.g. plastics, fiberglass or stainless steel. Important properties to be considered are pressure resistance, resistance towards corrosion, cleaning chemicals, temperature and vibration. Highly saline waters are very corrosive as is RO permeate if not further processed. High quality materials provide system integrity and reduce maintenance requirements. The preferred material for the high-pressure parts is stainless steel with low carbon content.

Properly calibrated and accurate control instruments are very important for sustained operation. Inaccurate instruments may lead to bad decisions by the operator due to wrong data, which could dramatically reduce system performance and lifetime. The following control instruments are considered essential:

Pressure gauges	before and after cartridge filter and membrane elements of each stage to monitor pressure drop
Flow meters	concentrate and total permeate flow rate, permeate flow rate of each stage
Conductivity meters	in feed line and permeate line to determine water quality and salt rejection

The following control instruments are highly recommended:

Water meters	feed and permeate line to log total water volume treated and produced
Hour meter	to log total operation time
pH meter	in the feed to assess carbonate scaling potential

Additionally sample ports on the feed, concentrate and permeate line as well as sample ports on each pressure vessels permeate outlet allow for the evaluation of system performance and facilitate troubleshooting.

4.3. NF VERSUS RO

NF and RO are two very similar processes. Most applications of desalination are of the RO type. However, when the removal of sodium and chloride is not of a high priority, NF can be a very effective low cost alternative [25]. The main difference of NF towards RO is its comparatively higher salt passage. This allows for higher membrane flux at lower pressures, which means that energy requirements are greatly reduced. As energy costs are the biggest factor in the operational expenses, overall treatment costs per m³ of permeate are less.

It is important to note, that the salt rejection of NF is selective. Generally, multivalent ions are rejected at a very high percentage, whereas monovalent ions such as sodium are rejected at a very low percentage. Nanofiltration membranes can also differ substantially in their salt rejection characteristics from one another. Very dense nanofiltration membranes can still reduce sodium concentration by 50%, whereas other may not significantly reduce sodium concentration. The rejection of sulfate, calcium, magnesium and other multivalent ions is generally high.

The applicability of nanofiltration therefore greatly depends on the feed water chemistry and the desired product water characteristic. Its application for brackish water of high salinity for the purpose of irrigation is questionable as in most cases the removal of sodium and chloride is the number one priority. For brackish water of low salinity, NF may be an attractive alternative. It may also be an advantage that the NF permeate may not require any posttreatment in the form of remineralization. While RO reduces the salt content of the water to an extent disadvantageous for irrigation, NF permeate may be suitable. In case another freshwater source is available and the product water is a blend of NF permeate with other water types, NF might also be attractive in replacing RO as a lower cost alternative even for feed water of higher salinity.

5. OPERATION AND MAINTENANCE

The goal of any operator is stable long-term performance with minimal operating cost. A good system design and value parts are basic preconditions. Another critical requirement is proper operation and maintenance. This includes proper start-up and shutdown sequences, monitoring, cleaning and record keeping as well as early detection and repairs of faulty equipment. In order to properly compare the data recorded from the plant, it is recommended to normalize the data. The normalization adjusts for the influence of temperature, variance in feed water composition, feed pressure etc., which allows for an early identification of potential problems.

5.1. GENERAL PERFORMANCE FACTORS

During operation, there are three main parameters, which influence plant performance, i.e. temperature, feed water salinity and pressure. Temperature and salinity are natural occurrences. Operating pressure can be adjusted and used to stabilize operation. All three parameters influence permeate salinity and quantity. An increase in temperature also increases the permeate flux, thus increasing recovery. At the same time, salt passage is also increased which means that less salt is rejected by the membrane. If feed water salinity is increased, the permeate flux decreases (reducing recovery) as well as the salt passage (less salt rejection). With increasing pressure, both permeate flux (recovery) and salt rejection can be increased. Figure 20 presents these basic relations.

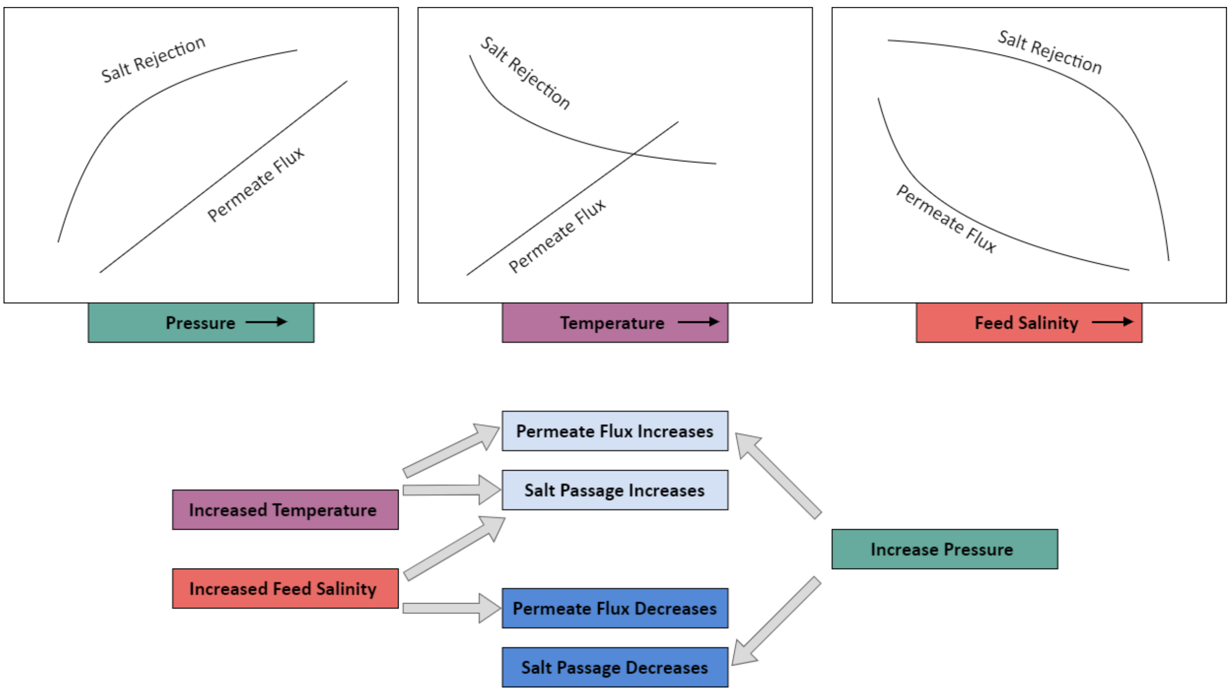


Figure 19: Basic relations of important performance parameters (adapted from DOW Technical Manual)

5.2. Start-up Sequence

A proper start-up sequence is supposed to prevent any damage to the membranes due to excessive pressure/flow or hydraulic shock as well as to prevent premature fouling and clogging due to unsuitable water quality. The first step therefore always is, to check for suitable water quality upon start of the raw water pump, which supplies the RO/NF treatment plant. If raw water quality is stable, the second step always is to flush the pretreatment section first and ensure proper functionality. Before opening the valves for the feed to enter the membrane section, the feed water should be stable with respect to flow, temperature and conductivity. There must be an absence of turbidity, chlorine and any other potentially damaging chemical agent. Only then, the membrane section may be flushed and the high pressure pump to be switched on. Special care must be taken if there is air within the pressure vessels. Air should be flushed out at a low flow rate and pressure. Increasing pressure too quickly may result in excessive forces inside the vessel and cause damage. Appendix 8.5 shows a typical Start-up sequence and Pre-start-up checklist taken from the technical manual of DOW.

The typical time-scale of the overall start-up sequence is 30 min up to 2 hours depending on the raw water quality. A normal start-up sequence can be considerably aided by using programmable controllers and remotely operated valves. RO/NF treatment plants are generally not designed for intermittent operation. Frequent start-stop-sequences wear on parts and membranes. Consequently, cost per m^3 of product water can substantially increase.

5.3. Shut-down Sequence

When the membrane system is shut down, no saline water should remain in the pressure vessels to prevent damage and fouling. Therefore the system has to be flushed with high quality feed water (preferably permeate) until the concentrate salinity matches the salinity of the feed. Flushing is carried out at low feed pressure, e.g. 3 bar, but higher flow rates can be beneficial for cleaning. Care must be taken, that the limit for maximum allowed pressure drop per vessel is not exceeded. If the system is of a multi-stage design, than the pressure vessels of the last stage normally experience the highest flow rates and have to be checked accordingly. After flushing is completed, no saline water should be able to enter the membrane system.

In case the feed/concentrate side is not flushed immediately after the high pressure pump had been switched off, the osmotic pressure difference induces a reverse flow through the membrane from the permeate side to the feed/concentrate side. This backflow may cause air to be sucked into the membrane system from the permeate side if the permeate tank does not accommodate sufficient water reserves. The backflow may have a light cleaning affect and will stop once an equilibrium is reached. However, saline water should not remain in the system. If the membrane system had been designed with a permeate backpressure, the membrane elements might be damaged after the high-pressure pump is switched off (see chapter 4.2.2). Care must be taken accordingly and safeguard valves should have been installed and operate properly.

During the time the system is shut down, the membranes must not be exposed to extreme temperatures (> 45°C) or dry out. A loss of water during the shutdown period may be caused by leakage or open concentrate or permeate lines. To prevent microbiological growth, the system should be flushed once per day or otherwise protected with appropriate chemicals, e.g. sodium bisulfite (SMBS). In case the system is not to be operated for more than 48 hours, the membrane elements should be preserved according to the manufacturer's recommendations, e.g. using a 1.5 % SMBS solution to protect from biofouling and irreversible loss of permeability.

5.4. OPERATION OF BRACKISH WATER DESALINATION SYSTEMS

The best way to operate a standard RO/NF-System for brackish water desalination is continuous operation with all parameters close to the design values, i.e. recovery and flow. Changes in flux due to temperature and fouling are compensated by adjusting the feed pressure. Running the plant over capacity, i.e. at higher permeate flow rate than it was designed for, is generally not recommended. In case the capacity needs to be reduced, shutting down the plant for a period of time is the simplest solution. However, intermittent operation with frequent shut downs reduce the lifetime of the plant and increase production costs. The capacity can also be reduced by reducing the feed pressure and thus reducing flow. To save energy, speed controlled pumps should be used. When reducing feed pressure, the system recovery usually is kept constant at the design value. However, the single element recovery then changes and should not exceed the limits given by the manufacturer to prevent severe fouling. The single element recovery can be calculated with special software often supplied by the membrane manufacturer.

Changes in the feed water composition may require altering all design parameters. In case water quality decreased and scaling potential increased, it may be required to lower system recovery. If the change in feed water composition is permanent, adjusting the system design may be appropriate, see Chapter 3. Changes in the feed water composition may also require a different choice in materials for piping and tanks.

5.5. RECORD KEEPING

Establishing a useful data record will prove very helpful in understanding ones RO/NF system, which in turn will lead to a better decision-making by the operator. Varying product requirements or feed water quality, faulty equipment, fouling and outside influences can then be handled in a more preventive approach. This will help in maintaining stable high performance and keep operational costs low.

When the RO/NF treatment plant is commissioned, all results of all performed checks should be recorded. Calibration curves of all instruments (gauges and meters) should be compiled according to manufacturer recommendations and all set points and values of all instruments of the initial performance of the membrane system as well as the pretreatment system should be recorded. This data provides a reference of system performance and a data set to compare future operational data with.

A daily log should be established with the following data:

General	Specific for each stage
Date, time and hours of operation	Pressure drop per filter cartridge and per stage
pH of the feed, permeate and concentrate streams	Feed, permeate and concentrate pressure
Silt Density Index (SDI) and/or turbidity of the RO feed stream	Permeate and concentrate flows
Water temperature of the feed stream	Conductivity of the feed, permeate and concentrate streams
Any unusual incidents, for example, upsets in SDI, pH and pressure and shutdowns	Permeate conductivity of each pressure vessel weekly.
	Conductivity/TDS of feed, permeate and concentrate streams

Conductivity & Temperature

Electrical conductivity is dependent on water temperature. It is common to use the EC25, i.e. conductivity at 25°C. Most instruments have a built in temperature sensor and the option to correct for temperature to show the EC25. If the EC25 is not used, then water temperature always has to be noted next to the conductivity value to be able to compare measurements.

Conductivity & TDS (k value)

The TDS can be calculated from the EC25 by multiplying it with an appropriate k value. However, k is dependent on the water composition and as such unique. Typical k values are in the range of 0.5 and 0.7 with the lower value corresponding to permeate and the higher value corresponding to concentrate. The exact TDS can also be calculated from the complete water analysis.

Instruments should be calibrated according to the specifications in method and frequency, e.g. every six months. The calibration curves can also be added to the log.

A complete raw water analysis had to be carried out to design the plant. It is recommended to repeat the feed water analysis at commission and in regular time intervals (e.g. monthly) thereafter. The water analysis shall include all major ions as well as TOC, pH and conductivity.

Table 8: Important parameters for a water analysis

Cations	Anions
Calcium	Bicarbonate
Magnesium	Sulfate
Sodium	Chloride
Potassium	Nitrate
Strontium	Fluoride
Barium	Phosphate (total)
Iron (total, dissolved and ferrous)	
Aluminum (total and dissolved)	Silica (dissolved)
Parameters	
Conductivity	
pH	
TOC	

Examples of water chemistry analysis of groundwater in the Lower Jordan Valley is given in chapter 2.1.

These recommendations are a general guidance only. Some units may not have all instruments at all places required to complete this log. Other factors are site dependent and the inclusion of further data may be necessary.

5.6. NORMALIZATION

The aim of normalization is to be able to distinguish changes in plant performance caused by natural phenomenon and changes due to fouling or other problems. A natural phenomenon for example is a rise in feed water temperature. An increase of 4 °C causes an increase of permeate flow of about 10%. Normalization eliminates the influences of the operating parameters by comparing the actual performance to a reference performance. This reference performance can be the designed system performance to compare whether the system does as it should or it can also be the initial system performance to show performance changes over time. Free software is available to compute normalized operating data using excel, e.g. FTNORM by DOW on filmtech.com.

Tracking plant performance with normalized operating data allows for early detection of potential problems such as scaling and fouling if recorded daily. Corrective measures are much more effective when taken early.

6. COST CONSIDERATIONS

RO/NF membrane desalination is an established state of the art technology and generally the most cost effective solution for brackish water desalination. However, any desalination technology is more cost intensive than traditional water treatment options, which rely on fresh ground and surface waters. Since these traditional water sources are increasingly exploited or unavailable, modern membrane desalination has become a viable option providing a supplementary water source. Advances in desalination technology over the past decades have enhanced membrane performance and reduced energy demand, the two most critical factors for economic performance. Furthermore, membrane costs as well as capital investment cost in general have been reduced as well. The good water quality provided by RO/NF desalination can increase crop efficiency when used for irrigation. When combined with crops of a high water value or other applications with a high return value per m^3 of desalinated water, economics can be favorable [3, 4]. For example, a study by the University of Jordan found cucumber and strawberries to have the highest water value of investigated crops identifying a water value of about JD 4.3 per m^3 of irrigation volume. The total cost per m^3 of desalinated water is estimated to be JD 0.226 in average.

Desalination costs can be divided into two major category groups, which are linked to a certain extent, capital investment and operational expenses (OPEX). Capital investment is comprised of the costs for materials, design and construction. Operational expenses are comprised of energy costs, maintenance, labor, articles of daily use, e.g. chemicals and replacements, e.g. membranes. Generally, a higher capital investment reduces operational costs for a number of reasons. Firstly, an optimally designed plant produces the same amount of quality product at smaller feed pressure and/or smaller feed flow rate, thus reducing energy costs, which are the biggest share of operational costs. A well-designed plant also has a good pretreatment system, which reduces the fouling potential, thus increasing membrane and general lifetime. Furthermore, quality materials of appropriate resistance to the harsh environment present inside a RO treatment plant increase general lifetime and reduce the risk of system failure. Reliable and accurate control instruments allow for optimal operation and reduce the risk of system failure. However, with increasing design quality, overall plant complexity is increased as well, which poses a greater challenge for operators. The qualification of operators has to meet the requirements of the plant. Otherwise, there is a risk that incorrect operation mitigates good design solutions with increased operational costs.

Another important factor is the operational time frame. RO/NF treatment plants are most cost efficient when operated continuously 24h per day throughout the year. Obviously, the design capacity of a desalination system, which supplements traditional water sources, has to meet the minimum demand during the times these traditional sources are insufficient. For the situation in the LJRV, this means that desalination systems are designed for water demand in the summer. During winter, running desalination systems continuously may result in producing water in excess, which then cannot be utilized economically since the demand can be covered with cheaper traditional sources. Hence, currently installed RO-Systems in Jordan are intermittently shut off for some time (approximately 3 month in accumulated total time) during winter. However, this scenario increases the overall cost per m³ of desalinated water and intermittent operation reduces the lifetime of RO-Systems. Instead, in a best-case scenario, excess product water could be used for alternative applications, which are still economically favorable, e.g. selling/trade or farming of high value crops with low tolerance for salinity or for environmental remediation, e.g. groundwater recharge.

Table 9: Model calculation to demonstrate the influence of capital investment and operational cost on efficiency and product cost

	Simple one-stage-system – simple pretreatment	Advanced two-stage-system – advanced pretreatment	Advanced two-stage-system – advanced pretreatment high value parts
Capital Investment	50,000	100,000	150,000
Product capacity [m³/year]	150,000	150,000	150,000
Product TDS	150 ppm	150 ppm	150 ppm
Recovery	60%	75%	75%
Feed flow [m³/year] Abstracted groundwater	250,000	200,000	200,000
Feed pressure	17 bar	14 bar	14 bar
Lifetime	10 years	20 years	20 years
Membrane replacement cycle	3 years	6 years	6 years
OPEX [%]	80%	70%	60%
OPEX [per year]	27,000	20,000	20,000
Price per m³	0.224	0.191	0.219

Initial investment costs are usually depreciated over a period of time and designated as fixed costs. The total monthly costs are the sum of these fixed costs and the operational costs. The projected operational timeframe should therefore be considered when evaluating the costs for desalination systems. An amortization time of 20 years is considered standard for RO/NF treatment plants. This means that the lifetime of an RO/NF treatment plant is expected to be at least 20 years. The lifetime of a desalination plant has a profound impact on the cost per m³ of desalinated water such that systems with a shorter lifetime have higher operating costs due to cheaper design, which results in a higher fouling propensity. Table 9 demonstrates the relation of initial investment cost and plant quality on product costs and other parameters. In this model scenario, product costs per m³ are not increased even though initial capital investment was tripled. This is because the model assumes a larger lifetime and less fouling due to better design. Operational costs are reduced by decreasing energy demand from lower feed pressure and higher recovery. Thus, significantly less raw water (20%) needs to be extracted from the deep groundwater aquifer, which also preserves the water source and produces less waste.

So far, any costs for brine disposal have been disregarded. For a sustainable implementation of brackish water desalination, precipitation of brine next to the station, discharge into a wadi or river or general land application are questionable solutions since they raise environmental concern and do not inactivate or remove brine from the region of application. Therefore, operators should allocate some costs toward a sustainable solution for brine disposal. In Jordan, the likely easiest and cheapest option would be the discharge of brine into the Dead Sea. Because of its unique characteristics, the environmental impact of the discharged brine should be minimal. In this scenario, brine would be collected from all stations using pipes or open channels and safely be transported towards the Dead Sea without the possibility of infiltrating the soil and groundwater aquifers in the region of application. The provision of infrastructure such a solution requires should also be in the interest of local authorities. Other options include business solutions such as fish farming and salt recovery or other disposal options such as solar evaporation (see chapter 3.6).

Opposite to costs for sustainable brine disposal are hidden costs, which are raised by the negative effects of brine remaining in the area of application. This means the costs, which are created by brine affecting soil and groundwater, thus raising salinity levels in connected aquifers, reducing soil value and fertility etc. These costs may not be imminent but can be pronounced in a scale of years. They also depend on the extent of desalination application. In 2016, the existing RO treatment plants operating on farms in the LJRV produced an estimated 4 to 5 million m³ of brine. This amount could potentially be doubled or tripled in the near future with 15 million m³ per year having a far greater impact on the environment if no sustainable disposal option is implemented.

The costs for appropriate brine disposal and the hidden costs are difficult to quantify since they are dependent on a number of variables and circumstances. Consequently, no estimation of these costs is given. Local authorities also play a large role by creating the framework for the application of desalination and specifically for brine disposal, e.g. whether application is regulated or not regulated, endorsement of good practice etc. The general (and safest) assumption is that brackish water desalination costs overall are minimized when negative impact on the environment in the area of application is also minimized.

6.1. COST ANALYSIS OF EXISTING RO-SYSTEMS IN JORDAN

This chapter presents some of the data gathered from currently operated RO-Units in the LJRV and serves as an example for the possibilities of the local market.

Farmers of the LJRV in Jordan have already begun implementing RO-Units 20 years ago. In 2016, more than 50 units are run privately. The local market is unregulated and therefore reliable data is scarce. The herein presented data was gathered during a visit by the authors and a survey conducted by the

University of Jordan. Table 10 presents some key points. Two points stand out. The average recovery is rather low at 65%. For brackish water desalination a recovery between 75% and 85% is to be expected. Furthermore, the average initial investment cost of about JD 65k ($ 92k) for an average plant capacity of 42 m³/h are very low too. This number is consistent with a statement of a local supplier of RO treatment plants in Amman, who stated costs of $ 2,000 per (m³/h) (JD 60k for 42 m³/h). At a recovery of 65%, the specific investment cost amount to JD 100 ($ 141) per (m³/day) of desalinated water. That is about 3 to 5-times less than expected from western markets [7, 13, 26-28].

Table 10: Cost analysis of RO treatment plants on farms in Jordan

Desalination in Jordan N = 46		Mean
Capacity	m³/h	42
Product Capacity	m³/h	27
Recovery	%	64
Capital Investment	US $	92,000
Capital Investment	JD	65,000
OPEX	%	76
OPEX	US $/a	39,500
OPEX	JD/a	28,000
Price per m³	US $/m³	0.32
Price per m³	JD/m³	0.226

The low capital costs in Jordan can be partially explained by the comparatively lower quality of systems. The capital costs also do not include costs in connection with the well, costs for connection with a grid and costs for the housing of the station. In many cases, a suitable well does already exist on a farm and the housing is generally of the most basic level with no climate control. An open pond next to the station serves as product storage and potential mixing tank. Many systems are single-stage, which explains the rather low average recovery. Control instruments are limited to few pressure sensors; one flow meter and one conductivity meter to assess permeate salinity. The pretreatment is generally limited to a sand filter, a cartridge filter and the addition of scale inhibitors based on synthetic phosphates and phosphonates. In some cases permeate salinity was elevated which indicates partial membrane failure. The survey conducted concludes that operational expenses represent about 80% of the total costs for desalination. Thus overall, the current practice in Jordan can be compared with scenario 1 in Table 9. This calculation concludes a desalination price of JD 0.226 ($ 0.319) per m³ of permeate in average. However, because of the variance in feed water quality, system quality as well as the quality of maintenance, the site specific costs per m³ of permeate can be substantially lower or higher.

7. GENERAL RECOMMENDATIONS

For the LJRV brackish water desalination is a very attractive solution. Its main benefit is the utilization of a previously unattractive water source, thus complementing the regions water stock for fresh water production. For entrepreneurs such as farmers investment in good quality desalination systems may be very beneficial. Economical evaluation demonstrates feasibility and the enhanced irrigation water quality increases yields due to reduced salinity stress. In addition, the apparent water scarcity in the LJRV would likely force regulators in the future to increase prices for traditional fresh water sources to increase the incentive for efficient water usage. Farmers which efficiently utilize brackish water desalination would likely profit from that scenario.

The downside of any inland application of desalination technology is the need for a sustainable management of the very saline by-product brine. Apart from its high salinity, brine also contains all chemicals added during the process, e.g. antiscalant or cleaning chemicals. If not removed from the area of application, brine causes an increase of groundwater salinity and decreases soil value. Brine as a waste is also very mobile which means that it can affect a large area even when only discharged at local points. In an area used for agriculture any discharge of brine into the soil therefore stresses two very important foundations, soil and raw water quality. Brine should be discharged to sea or otherwise managed by creative and innovative approaches (see chapter 3.6).

The abilities of the local market and the qualification of operators play a large role on the type of systems, which can be implemented. In Jordan, the market supports a large variety of systems from low priced simple solutions to high priced complex ones. Because of the water scarcity in the region, the general aim should be to maximize recovery, which means an investment in more complex solutions. This also requires general planning to shift to a larger timeframe considering RO desalination to be a permanent installation.

Maintenance and operation are important in keeping production costs low and maximizing the lifetime of the plant. Leakages, broken membranes, clogged filters, unsuitable raw water quality etc. should not be tolerated. Chemicals should be handled carefully and appropriately. Acid fumes from an unclosed acid canister for example can cause corrosion to the plant and important parts e.g. the high-pressure pump. Furthermore, acid fumes present a serious health hazard for operators. Operator safety should always be a priority.

The importance of record keeping cannot be over-emphasized. Good records provide the base for the growth in knowledge and experience. Systems can be optimized and future systems can be designed to be more efficient. During operation, good records facilitate troubleshooting and aid in operating the plant at optimal efficiency. Performing a membrane autopsy on old membrane elements can clarify the main causes of fouling and preventive measures can be installed.

Table 11: General recommendations (photos: Oliver Jung)

	Provide suitable housing to protect desalination systems from direct sunlight and extreme temperatures. Have adequate pretreatment. Consider increasing system recovery to increase efficiency and reduce groundwater abstraction. Quality parts and materials increase lifetime and reduce maintenance. Avoid frequent start-ups and shutdowns.
 	Shallow and open storage ponds introduce contaminants and lose product water due to evaporation (evaporation capacity up to 2600 mm/a). Closed tanks preserve expensive permeate.
	Consider treatment and adequate disposal of the very saline brine to prevent degradation of soil and groundwater.
 	Maintenance and good operation practices keep production cost low and ensure safety for the operators. Leakages, open chemical tanks, loose and damaged parts should not be tolerated and may reduce system integrity and lifetime as well as diminish product quality. Keep records of system performance and normalize your data to facilitate troubleshooting.

8. APPENDIX

8.1. SELECTED WATER DATA FROM SAMPLES COLLECTED IN JORDAN

Farm 1		Feed	Permeate	Brine
pH (30°C)		6.9	5.7	7.3
El. conductivity (25°C)	mS/cm	5.35	0.37	16.62
DOC	mg/L	2.3	n.a.	4.8
Calcium	mg/L	241	3.6	600
Potassium	mg/L	46	4.5	165
Magnesium	mg/L	184	2.2	570
Sodium	mg/L	632	63.1	2004
Chloride	mg/L	1608	77.5	4900
Sulfate	mg/L	795	6.8	1829

Farm 2		Feed	Permeate	Brine
pH (30°C)		7.0	6.5	n.a.
El. conductivity (25°C)	mS/cm	3.83	0.50	8.8
DOC	mg/L	1.1	n.a.	9.3
Calcium	mg/L	110	4.3	161
Potassium	mg/L	67	8.6	172
Magnesium	mg/L	110	4.6	276
Sodium	mg/L	514	88.2	1155
Chloride	mg/L	1073	124.2	2400
Sulfate	mg/L	532	10.5	500

Farm 3		Feed	Permeate	Brine
pH (30°C)		6.7	6.9	7.0
El. conductivity (25°C)	mS/cm	11.53	5.88	13.21
DOC	mg/L	7.34	2.9	5.8
Calcium	mg/L	482	236	600
Potassium	mg/L	137	64.9	147
Magnesium	mg/L	379	195	470
Sodium	mg/L	1334	714	1501
Chloride	mg/L	3363	1636	3900
Sulfate	mg/L	700	684	1200

Farm 4		Feed	Permeate	Brine
pH (30°C)		n.a.	n.a.	n.s.
El. conductivity (25°C)	mS/cm	4.39	0.54	n.s.
DOC	mg/L	1.6	n.a.	n.s.
Calcium	mg/L	212	10.6	n.s.
Potassium	mg/L	49	7.8	n.s.
Magnesium	mg/L	162	8.8	n.s.
Sodium	mg/L	520	77.0	n.s.
Chloride	mg/L	1161	124.1	n.s.
Sulfate	mg/L	660	19.5	n.s.

Farm 5		Feed	Permeate	Brine
pH (30°C)		6.8	5.8	7.1
El. conductivity (25°C)	mS/cm	7.89	0.52	12.78
DOC	mg/L	1.9	n.a.	4.0
Calcium	mg/L	321	8.2	549
Potassium	mg/L	87	7.0	147
Magnesium	mg/L	240	7.5	399
Sodium	mg/L	994	75.0	1614
Chloride	mg/L	2124	125.9	3502
Sulfate	mg/L	724	14.6	963

Farm 6		Feed	Permeate	Brine
pH (30°C)		6.8	6.0	7.1
El. conductivity (25°C)	**mS/cm**	5.8	0.95	12.3
DOC	mg/L	2.2	n.a.	4.0
Calcium	mg/L	296	22.9	710
Potassium	mg/L	57	14.6	128
Magnesium	mg/L	244	22.6	580
Sodium	mg/L	605	125.4	1291
Chloride	mg/L	1401	499	3391
Sulfate	mg/L	906	61.7	1889

Farm 7		Feed	Permeate	Brine
pH (30°C)		6.8	5.9	6.8
El. conductivity (25°C)	**mS/cm**	6.54	0.72	18.81
DOC	mg/L	2.0	n.a.	7.7
Calcium	mg/L	300	5.1	750
Potassium	mg/L	116	12.4	253
Magnesium	mg/L	220	4.0	615
Sodium	mg/L	790	125.1	2220
Chloride	mg/L	1690	171.3	5874
Sulfate	mg/L	600	10.6	1700

n.a.: not analyzed

n.s.: no sample available

8.2. ROSA-SIMULATION

RO membrane simulation software such as ROSA (DOW), Toray DS, WinFlows (GE) etc. are able to calculate the expected performance parameters of a certain RO treatment plant. This allows for the optimization of system design. The important input parameters are the water analysis, the desired recovery and the desired permeate flow rate. The software then allows to look at different layouts and see how performance values change to identify an optimal design. The following tables show examples of such calculations with a two-stage-system. The water data was taken from a farm in Jordan with an above average salinity.

The results were obtained by following the steps suggested by the DOW Technical Manual [8] and using the tables provided. The following design parameters were selected:

Input water type = well water, SDI < 3

Selected flux = 22 l/m²h

Number of elements = 36

Number of elements per vessel = 6

Total Number of pressure vessels = 6

Two stages

Staging Ratio = 2:1

Note how feed pressure, recovery and permeate flow change for each single element when the water temperature changes (Figure 20 vs. Figure 21). Also, note that the LSI in the concentrate is greater zero and that the saturation of barium sulphate and calcium fluoride is greater than 100%. This means that scaling of calcium carbonate, barium sulfate and calcium fluoride is to be expected if no antiscalant is added.

System Details

Feed Flow to Stage 1	40.00 m³/h	Pass 1 Permeate Flow	30.00 m³/h	Osmotic Pressure:	
Raw Water Flow to System	40.00 m³/h	Pass 1 Recovery	75.00 %	Feed	2.56 bar
Feed Pressure	18.93 bar	Feed Temperature	20.0 C	Concentrate	9.68 bar
Flow Factor	0.85	Feed TDS	4245.34 mg/l	Average	6.12 bar
Chem. Dose (100% H2SO4)	0.00 mg/l	Number of Elements	36	Average NDP	12.73 bar
Total Active Area	1337.76 M²	Average Pass 1 Flux	22.43 lmh	Power	26.30 kW
Water Classification: Well Water SDI < 3				Specific Energy	0.88 kWh/m³

Stage	Element	#PV	#Ele	Feed Flow (m³/h)	Feed Press (bar)	Recirc Flow (m³/h)	Conc Flow (m³/h)	Conc Press (bar)	Perm Flow (m³/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	BW30-400/34i	4	6	40.00	18.58	0.00	18.71	17.78	21.29	23.88	3.50	0.00	46.81
2	BW30-400/34i	2	6	18.71	17.44	0.00	10.00	16.67	8.71	19.52	0.00	0.00	102.70

Pass Streams (mg/l as Ion)							
Name	Feed	Adjusted Feed	Concentrate		Permeate		
			Stage 1	Stage 2	Stage 1	Stage 2	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	115.70	115.70	244.08	451.04	2.93	6.37	3.93
Na	790.00	790.00	1678.94	3122.40	9.12	21.02	12.57
Mg	220.00	220.00	469.00	874.81	1.27	2.89	1.74
Ca	300.00	300.00	639.60	1193.10	1.68	3.85	2.31
Sr	4.60	4.60	9.81	18.29	0.03	0.06	0.04
Ba	0.04	0.04	0.09	0.18	0.00	0.00	0.00
CO3	0.33	0.33	2.04	9.54	0.00	0.00	0.00
HCO3	300.00	300.00	634.39	1167.58	4.18	8.78	5.49
NO3	20.90	20.90	40.14	67.90	4.00	8.26	5.23
Cl	1866.91	1867.00	3972.84	7397.22	17.14	39.68	23.68
F	1.30	1.30	2.76	5.13	0.02	0.04	0.02
SO4	600.00	600.00	1280.29	2390.23	2.40	5.45	3.29
SiO2	18.60	18.60	39.64	73.92	0.11	0.27	0.16
Boron	1.20	1.20	1.79	2.42	0.69	1.05	0.79
CO2	47.28	47.28	48.11	51.59	47.18	48.83	47.68
TDS	4245.25	4245.34	9023.83	16785.18	46.81	102.70	63.00
pH	6.80	6.80	7.04	7.19	5.17	5.46	5.27

Stage Details

Stage 1 Element	Recovery	Perm Flow (m³/h)	Perm TDS (mg/l)	Feed Flow (m³/h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.10	1.02	30.54	10.00	4245.34	18.58
2	0.11	0.97	35.44	8.98	4723.78	18.38
3	0.12	0.92	41.60	8.01	5293.19	18.21
4	0.12	0.87	49.48	7.09	5976.82	18.07
5	0.13	0.81	59.81	6.22	6803.45	17.95
6	0.14	0.74	73.69	5.41	7807.00	17.86

Stage 2 Element	Recovery	Perm Flow (m³/h)	Perm TDS (mg/l)	Feed Flow (m³/h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.10	0.92	66.17	9.35	9023.83	17.44
2	0.10	0.84	77.92	8.44	9995.70	17.25
3	0.10	0.77	92.81	7.59	11098.82	17.10
4	0.10	0.69	111.94	6.82	12339.46	16.96
5	0.10	0.61	136.80	6.13	13714.62	16.85
6	0.10	0.53	169.32	5.52	15207.43	16.75

Figure 20: ROSA simulation report for a feed water temperature of 20 °C

System Details

Feed Flow to Stage 1	40.00 m³/h	Pass 1 Permeate Flow	30.00 m³/h	Osmotic Pressure:	
Raw Water Flow to System	40.00 m³/h	Pass 1 Recovery	75.01 %	Feed	2.65 bar
Feed Pressure	15.75 bar	Feed Temperature	30.0 C	Concentrate	9.94 bar
Flow Factor	0.85	Feed TDS	4245.34 mg/l	Average	6.29 bar
Chem. Dose (100% H2SO4)	0.00 mg/l	Number of Elements	36	Average NDP	9.46 bar
Total Active Area	1337.76 M²	Average Pass 1 Flux	22.43 lmh	Power	21.88 kW
Water Classification: Well Water SDI < 3				Specific Energy	0.73 kWh/m³

Stage	Element	#PV	#Ele	Feed Flow (m³/h)	Feed Press (bar)	Recirc Flow (m³/h)	Conc Flow (m³/h)	Conc Press (bar)	Perm Flow (m³/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	BW30-400/34i	4	6	40.00	15.40	0.00	18.17	14.71	21.83	24.47	3.50	0.00	81.33
2	BW30-400/34i	2	6	18.17	14.37	0.00	10.00	13.72	8.18	18.34	0.00	0.00	190.77

Pass Streams (mg/l as Ion)							
Name	Feed	Adjusted Feed	Concentrate		Permeate		
			Stage 1	Stage 2	Stage 1	Stage 2	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	115.70	115.70	248.67	443.01	4.99	11.13	6.66
Na	790.00	790.01	1719.00	3091.91	16.53	40.83	23.16
Mg	220.00	220.00	481.46	870.74	2.31	5.62	3.21
Ca	300.00	300.00	656.64	1187.69	3.07	7.51	4.28
Sr	4.60	4.60	10.07	18.21	0.05	0.12	0.07
Ba	0.04	0.04	0.10	0.17	0.00	0.00	0.00
CO3	0.42	0.42	2.77	12.03	0.00	0.00	0.00
HCO3	300.00	300.00	648.21	1150.71	7.09	16.69	9.68
NO3	20.90	20.90	38.13	58.48	6.55	13.26	8.38
Cl	1866.91	1866.91	4071.73	7339.30	31.21	77.60	43.85
F	1.30	1.30	2.82	5.07	0.03	0.08	0.04
SO4	600.00	600.00	1315.39	2382.80	4.38	10.63	6.08
SiO2	18.60	18.60	40.69	73.54	0.21	0.54	0.30
Boron	1.20	1.20	1.61	1.96	0.86	1.18	0.95
CO2	41.62	41.62	42.76	47.01	41.70	43.76	42.28
TDS	4245.33	4245.34	9244.88	16644.85	81.33	190.77	111.13
pH	6.80	6.80	7.04	7.17	5.38	5.71	5.50

Design Warnings

-None-

Solubility Warnings

Langelier Saturation Index > 0
Stiff & Davis Stability Index > 0
BaSO4 (% Saturation) > 100%
CaF2 (% Saturation) > 100%
Antiscalants may be required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.

Stage Details

Stage 1 Element	Recovery	Perm Flow (m³/h)	Perm TDS (mg/l)	Feed Flow (m³/h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.11	1.12	49.81	10.00	4245.34	15.40
2	0.12	1.04	59.41	8.88	4772.16	15.23
3	0.12	0.96	71.77	7.84	5397.33	15.08
4	0.13	0.87	87.95	6.88	6140.42	14.96
5	0.13	0.78	109.57	6.01	7021.25	14.86
6	0.13	0.68	139.06	5.23	8055.05	14.78
Stage 2 Element	Recovery	Perm Flow (m³/h)	Perm TDS (mg/l)	Feed Flow (m³/h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.10	0.95	115.04	9.09	9244.88	14.37
2	0.10	0.84	140.34	8.14	10308.67	14.21
3	0.10	0.73	173.30	7.30	11478.99	14.08
4	0.09	0.62	216.70	6.57	12736.65	13.97
5	0.09	0.52	273.97	5.94	14047.61	13.87
6	0.08	0.43	349.59	5.42	15366.91	13.79

Scaling Calculations

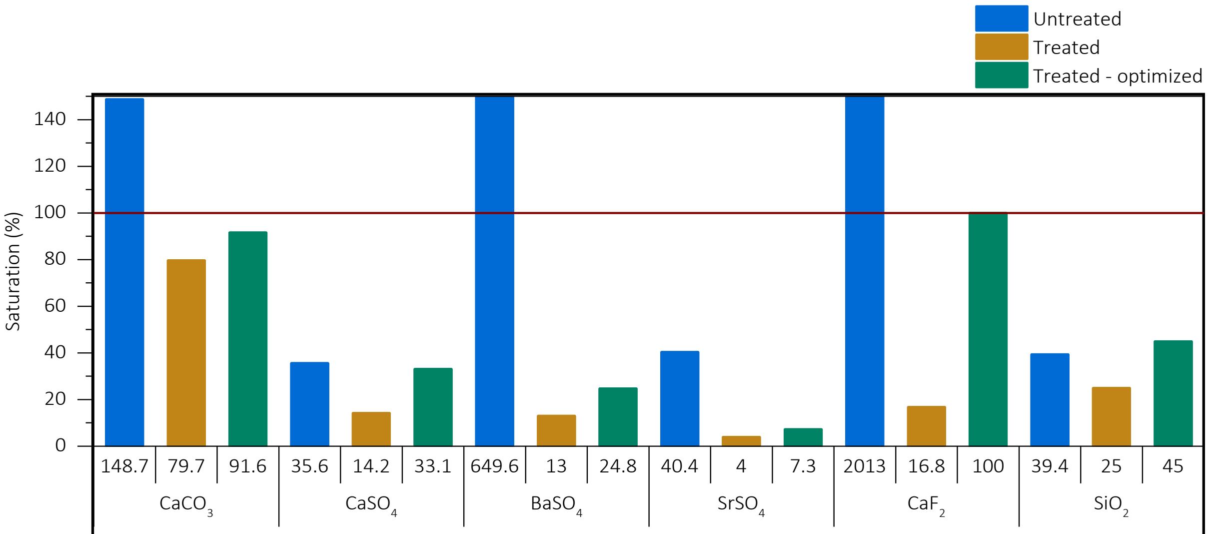
	Raw Water	Adjusted Feed	Concentrate
pH	6.80	6.80	7.17
Langelier Saturation Index	0.21	0.21	1.73
Stiff & Davis Stability Index	-0.01	-0.01	0.98
Ionic Strength (Molal)	0.09	0.09	0.37
TDS (mg/l)	4245.33	4245.34	16644.85
HCO3	300.00	300.00	1150.71
CO2	41.62	41.62	47.00
CO3	0.42	0.42	12.03
CaSO4 (% Saturation)	16.55	16.55	86.84
BaSO4 (% Saturation)	225.03	225.03	917.69
SrSO4 (% Saturation)	11.58	11.58	51.26
CaF2 (% Saturation)	67.40	67.40	4054.49
SiO2 (% Saturation)	13.43	13.43	54.47
Mg(OH)2 (% Saturation)	0.00	0.00	0.01

Figure 21: ROSA simulation report for a feed water temperature of 30 °C

8.3. ASSESSING MAXIMUM RECOVERY USING ANTISCALANT SOFTWARE

In brackish water desalination, maximum recovery is mostly set by the fouling tendency of the feed water. Scaling is one of the main contributors to fouling. Scaling inhibitors are able to keep salts in solution and raise the limit of maximum recovery. Figure 22, calculated with an antiscalant dosing software, demonstrates the effect of scaling inhibitors.

Also, note the daily requirements of antiscalant. Because the antiscalant concentration in the brine is the relevant parameter, the daily requirement is reduced at higher recovery as less brine is being generated. The water data is taken from a farm in Jordan. It is the same one, which was used for the ROSA simulation. The recovery was increased until the saturation of one constituent reached 100% (CaF_2). The calculation software shows a maximum recovery of about 80% at which scale formation can still be controlled.



		Untreated	Treated	Treated optimized
Recovery	%	75	65	80.7
Feed water dose	mg/L	0	3.32	2.23
Daily requirement	kg	0	3.68	1.99
Permeate Flow	m³/h	30	30	30

Figure 22: Saturation of low soluble salts in brine at varying recovery and antiscalant dosing

8.4. PRELIMINARY FACT SHEET

The following is an example of a preliminary fact sheet to commence with system design as recommended by DOW Technical Manual

Quotation Number: .... Date Requested: ....

Date Submitted: .... Requested By: ....

Customer/OEM: ....

Address: ....

Proposed Location: ....

Brief Description: ....

....

Required Product Flowrate (gpd or m^3/h): ....

Expected Recovery: ....

Annual Water Temperature Range: High °C: ....

Low °C: ....

Design °C: ....

NF/RO Plant: ❑Indoors ❑Outdoors

Designed for Continuous Use: ❑Yes ❑No

If not, state needed peak hourly capacity: ....

Plant Will Be Operated By:			
	Enduser	❑Yes	❑No
	Trained Personnel	❑Yes	❑No
	Equipment Manufacturer	❑Yes	❑No
	Others	❑Yes	❑No

Water Source: ❑Well Water ❑Softened water ❑Surface Water ❑Filtered Effluent Water ❑Sea Water ❑Other

Existing Pretreatment ❑Yes ❑No

SDI: ....

Planned Pretreatment:

List of Pretreatment Steps:

....

....

....

Bacterial Control:	❑Yes	❑No	Dechlorination: ❑Ac-Filter
Chlorine Used	❑Yes	❑No	❑Na-Bisulfite
Chloramines Used:	❑Yes	❑No	❑Other
Antiscalant Used:	❑Yes	❑No	Which One? ....
Desired Acidification:	❑HCl	❑H_2SO_4	❑None

Brief Description of Other Pretreatment Steps: ....

(e.g., clarification, flocculation, multimedia/sand filtration, etc)..

....

Application: ❑Potable Water

❑Industrial Supply for: ❑Boiler Feed ❑Pharma ❑Electronics ❑Other

Specify Water Quality Needed after RO Treatment: ....

State Other Desired Design Criteria: ....

Water Analysis

Sample identification: ....

Feed source: ....

Conductivity: .... pH: .... Temperature (°C): ....

Feed water analysis:
Please indicate units (mg/L as ion or ppm as $CaCO_3$ or meq/L)

NH_4^+	CO_2 ....
K^+	CO_3^{2-} ....
Na^+	HCO_3^- ....
Mg^{2+}	NO_3^- ....
Ca^{2+}	Cl^- ....
Ba^{2+}	F^- ....
Sr^{2+}	SO_4^{2-} ....
Fe^{2+}	PO_4^{3-} ....
Fe (tot)	S^{2-} ....
Mn^{2+}	SiO_2 (colloidal) ....
Boron	SiO_2 (soluble) ....
Al^{3+}	

Other ions: ....
....
....

TDS (by method): ....

TOC: ....

BOD: ....

COD: ....

AOC: ....

BDOC: ....

Total alkalinity (m-value): ....

Carbonate alkalinity (p-value): ....

Total hardness: ....

Turbidity (NTU): ....

Silt density index (SDI): ....

Bacteria (count/mL): ....

Free chlorine:..

Remarks: ....

(odor, smell, color, biological activity, etc.) ....

Analysis by: ....

Date: ....

8.5. START-UP SEQUENCE CHECKLIST

The following is a start-up checklist as recommended by DOW Technical Manual.

Proper start-up is important to not damage the plant and to prevent the intrusion of unsuitable feed water, which can exacerbate fouling or even cause clogging.

(1) Rinse pretreatment section to flush out debris and other contaminants

(2) Check all valves to ensure that settings are correct. Open feed pressure control and concentrate control valves.

(3) Use low-pressure water at a low flowrate to flush the air out of the elements and pressure vessels. Flush at a gauge pressure of 2 – 4 bar (Air inside pressure vessels may damage them if the pressure is raised too quickly). All permeate and concentrate flows should be directed to an appropriate waste collection drain during flushing.

(4) During the flushing operation, check all pipe connections and valves for leaks.

(5) After the system has been flushed for a minimum of 30 minutes, close the feed pressure control valve.

(6) Ensure that the concentrate control valve is open.

Starting against a closed or almost closed concentrate valve could cause the recovery to be exceeded, which may lead to scaling.

(7) Slowly crack open the feed pressure control valve (feed pressure should be less than 4 bar.

(8) Start the high-pressure pump.

(9) Slowly open the feed pressure control valve, increasing the feed pressure and feed flowrate to the membrane elements until the design concentrate flow is reached. The feed pressure increase to the elements should be less than 700 mbar per second to achieve a soft start. Continue to send all permeate and concentrate flows to an appropriate waste collection drain.

(10) Slowly close the concentrate control valve until the ratio of permeate flow to concentrate flow approaches, but does not exceed, the design ratio (recovery). Continue to check the system pressure to ensure that it does not exceed the upper design limit.

(11) Repeat steps (9) and (10) until the design permeate and concentrate flows are obtained.

(12) Calculate the system recovery and compare it to the system's design value.

(13) Check the addition of pretreatment chemicals (acid, scale inhibitor and sodium metabisulfite if used). Measure feedwater pH.

(14) Check the Langelier Saturation Index (LSI) of the concentrate by measuring pH, conductivity, calcium hardness, and alkalinity levels and then making the necessary calculations.

(15) Allow the system to run for one hour.

(16) Take the first reading of all operating parameters.

(17) Check the permeate conductivity from each pressure vessel to verify that all vessels conform to performance expectations (e.g., vessels with leaking O-rings or other evidence of malfunction to be identified for corrective action).

(18) After 24 – 48 hours of operation, review all recorded plant operating data such as feed pressure, differential pressure, temperature, flows, recovery and conductivity. At the same time draw samples of feedwater, concentrate and permeate for analysis of constituents.

(19) Compare system performance to design values.

(20) Confirm proper operation of mechanical and instrumental safety devices.

(21) Switch the permeate flow from drain to the normal service position.

(22) Lock the system into automatic operation.

(23) Use the initial system performance information obtained in steps (16) through (18) as a reference for evaluating future system performance. Measure system performance regularly during the first week of operation to check for proper performance during this critical initial stage.

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